How threatened are plants?

Assessing conservation status of plants to support global conservation targets

Steven Philip Bachman

Thesis submitted to the University of Nottingham

for the degree of Doctor of Philosophy

August 2017

Supervisors: Dr. Richard Field & Dr. Tom Reader (Nottingham University)

External supervisor: Dr. Matthew Smith (Microsoft)

Internal Examiner: Dr. Adam Algar (Nottingham University)

PhD Nottingham University (commenced July 2015)

(APEL in place of year 1)

Acknowledgements

First, I would like to thank the Royal Botanic Gardens, Kew for supporting this PhD, it may never have happened otherwise.

I thank Nottingham University and my supervisors Dr Richard Field and Dr Tom Reader for being game enough to take on this PhD. Your flexibility, patience, encouragement and advice have helped to keep me on track, and I'm grateful for all your support. I also thank Dr Matthew Smith for many thoughtful and inspiring conversations whilst preparing this thesis.

Thank you to Dr Eimear Nic Lughadha for managing me through an unmanageable period, and for advice and guidance. Thanks to Justin Moat for many years of mentoring, support and inspiration and for taking a chance on me many years ago.

I am indebted to the numerous co-authors that have contributed to the papers included in this thesis. Some of you have needed to be very patient and I thank you for that, and I hope you agree it was worth it in the end. My eternal thanks go to all generations of the SRLI team – what a team! Your hard work and dedication created something special and you continue to inspire me.

Special thanks also to Don Doering at JRS Biodiversity Foundation. Your flexibility with the Madagascar Threats project allowed me to balance my workload and I appreciate your generosity.

A big thank you to the team at IUCN, especially Craig Hilton-Taylor for many years of advice on all things Red List related.

I'd like to acknowledge my friends from the Brunel Geography class of '99 for helping to put me on this path and for encouragement to stick with it. Finally, a special thank you to my family for believing in me and for many years of love and support. And most of all, to Sara – minha companheira ;) – if I made it this far, it's only because you are by my side.

Abstract

This thesis aims to gain a more quantitative answer to the question: 'How threatened are plants?' Plants make up a large component of the world's biota but are suffering as a result of pressures from anthropogenic activities including land cover change, over-consumption of plant resources and stresses associated with a changing climate. Loss of plants, either in terms of reduction in abundance or in the extreme case, extinction of species, will reduce the stability of ecosystems, and will potentially cause the collapse of ecosystems. Insufficient resources are available to protect all plants and a process of prioritisation is therefore needed to stem the losses resulting from anthropogenic activities.

To support prioritisation we need to know which are the most important species and sites to protect and this could be determined by the density of species in an area, the usefulness of a species, the functional role a species plays in an ecosystem as well as the costs likely to be incurred to undertake protection. However, we also need to know the urgency with which we need to act. By assessing the threat status of species we can better understand both the level of exposure to threatening processes and how sensitive a species is to these threats. Conservation planning that does not consider threat status can be compromised because long-term persistence of threatened species is not guaranteed. In this thesis, I discuss the assessment of threat status at the species level in the context of conservation narratives and target-setting. I then make a series of specific advances with respect to improving global knowledge of threats to plant species as follows.

As well as directly supporting conservation prioritisation efforts, threat status and trends in threat status have been incorporated into global biodiversity and conservation targets. The IUCN Red List framework for assessing threat status, or more specifically, risk of extinction, has been used to respond to the 2010 Biodiversity Target. I applied the Red List methodology to a random sample of c. 4,000 plants from the monocot, gymnosperm and pteridophyte clades, and legume family, of which 21.5% were threatened with extinction. Using the Red List framework means this approach can be compared to other groups; this indicates that plants are as threatened as mammals, more threatened than birds, but not as threatened as amphibians. Furthermore, the status of species can be reassessed to determine trends in extinction risk over time in support of renewed conservation targets.

Conservation targets have been set specifically for plants, such as the Global Strategy for Plant Conservation (GSPC), and threat status features heavily in a specific target (GSPC Target 2), as well as being incorporated into many other targets. A quantitative response to GSPC Target 2 had been lacking until now. Here I present the most comprehensive synthesis of plant threat status assessments, showing that as many as 30,000 plant species have been assessed as threatened at the global scale. Furthermore, with only about a quarter of plant species assessed, there is a large gap in the knowledge of threat status for plants.

Acknowledging that gaps in plant threat status knowledge could limit conservation efforts, it is necessary to speed up the process of assessment, without compromising assessment quality. Despite little evidence that trends in assessment production have increased in recent years, I review recent developments and identify ongoing challenges to progress. I conclude that there are good opportunities, such as the exploitation of technological developments, to close the knowledge gap much more quickly.

Overall, this thesis provides new information on the level of threats that plants face and sets baselines from which trends can be monitored. It includes a quantitative response to a key global conservation target (GSPC Target 2). Further work should now focus on closing remaining knowledge gaps, to ensure that opportunities for plant conservation are not lost.

The Extinction Symbol – see http://www.extinctionsymbol.info/

A population of *Tillandsia latifolia* Meyen in the San Fernando Reserve, Ica, Peru. Currently rated as Least Concern (LC) on the IUCN Red List, but this population had recently been dissected by a road leading to the Marcona Mine, the road runs from the left to the centre of the image. The mine sits on top of one of the largest iron ore reserves in the world.

List of Abbreviations

AOO	Area of occupancy
AZE	Area of Zero Extinction
BGCI	Botanic Gardens Conservation International
CBD	Convention on Biological Diversity
DAI	Digitally Accessible Information
EOO	Extent of occurrence
GBIF	Global Biodiversity Information Facility
GSPC	Global Strategy for Plant Conservation
IUCN	International Union for the Conservation of Nature
KBA	Key Biodiversity Area
PA	Protected Area
RBG	Kew Royal Botanic Gardens, Kew
RLI	Red List Index
SDG	Sustainable Development Goals
SRLI	Sampled Red List Index
SSC	Species Survival Commission (of the IUCN)
UNEP	United Nations Environment Program

Table of Contents

A. Synthesis/Extended abstract

This synthesis/extended abstract is an integrative chapter aiming to contextualise, and serve as a guide through, the research and outcomes of the papers in my PhD thesis. First, I provide an overview of relevant literature, which describes the background and context to the themes of my research and establishes the gaps in knowledge that I have addressed. I describe how conservation assessments, including assessments of extinction risk using the IUCN Red List categories and criteria, have been used to support conservation actions and to track progress against conservation targets. The strengths and weaknesses of the IUCN Red List approach are also discussed. I then formalise the aims of my research and the specific research questions that each paper focuses on. I then reflect on, and critically evaluate, the methods and techniques applied throughout the research. I conclude by discussing how well my papers answered the initial research questions, what impact the limitations had, and where future work should be directed. This synthesis/extended abstract (section A) is followed by the published and un-published papers (section B) and, all relevant supplementary work is included as an appendix to the thesis in section C.

i) Literature review

Each of the published and un-published papers in section B includes an introduction that puts the issues being addressed in each paper into context. However, these introductions are specific to each paper, assume existing knowledge on the use of Red List assessments for plants and are constrained by journal word count limitations. A broader overview is therefore necessary to set the scene for all four papers included in this thesis. This literature review provides a broad overview of the scientific underpinnings of the Anthropocene biodiversity crisis and the response of the conservation community, with a particular focus on the role of conversation status assessments and conservation targets.

Holocene humans and the dawn of the Anthropocene

The geological epoch spanning the last ~11.7 thousand years is known as the Holocene (Walker et al. 2009). The Holocene is notable as the period in which humans (*Homo sapiens*) transitioned from being disparate bands of hunter-gatherers, with a global population of ~10 million individuals, to the most dominant and influential species on the planet, with a population of ~7.6 billion (Steffen et al. 2004). The increasing activity of humans throughout the Holocene, and the mark this has left on the Earth's terrestrial, marine and atmospheric systems, is now considered enough to define a new epoch: the Anthropocene (Crutzen 2002).

Humans interact with and influence the environment and species around them, just like any other species, including earlier hominids. Indeed, the ancestors of the Holocene humans, those from the previous Quaternary era, are hypothesised to have impacted the biodiversity around them in various ways, including causing the extinctions of other species (Koch and Barnosky 2006). Most of the large animals, or megafauna, of the late Quaternary period became extinct either wholly or partly as a result of humans, through over-hunting or indirect effects such as habitat alteration or fragmentation (Koch and Barnosky 2006). This led to downstream impacts on the functioning and structure of ecosystems (Johnson 2009), in some cases triggering permanent ecosystem shifts (Rule et al. 2012). However, just as much as humans were influencing the environment, the environment was simultaneously influencing humans through changes in environmental stresses such as pathogens and fluctuations in net primary productivity (Tallavaara et al. 2018). The Holocene, in contrast, is a unique period for humanity because it marks a turning point where the interplay of human activity and environmental feedbacks drifted out of balance as humans became the overwhelmingly dominant force on the Earth (Steffen et al. 2007).

The extent and scale of human impact increased dramatically as humans transitioned from hunter-gatherer, to agricultural, industrial and then urbanised societies (Steffen et al. 2015a). The exact point at which these changes signalled a shift from the Holocene to a new epoch, known colloquially, but not yet formally, as the Anthropocene is debated (Crutzen 2002; Balter 2013; Waters et al. 2016). Analysis of human influence on terrestrial biomes suggests that at the start of the Holocene the majority of the Earth's biomes were in a natural or 'wildland' state, whereas the reverse was true by the year 2000 with the majority of biomes showing evidence of substantial human influence – also referred to as anthropic biomes or 'Anthromes' (Ellis and Ramankutty 2008; Ellis 2011). A period of particularly rapid change is apparent throughout the latter half of the 20th Century and is known as 'The Great Acceleration' (Steffen et al. 2015a).

The Great Acceleration – indicators of the Anthropocene

Indicators can be used to track both changes in human activities and changes in the Earth's biological and climatic systems (Steffen et al. 2015a). Where data exist, socio-economic indicators such as urban population size and primary energy use tend to show steady increases over the last ~250 years and then a marked acceleration around the year 1950 (Figure 1). The pattern is similar for indicators relating to earth systems and land use, although a 1950 acceleration is less apparent; for example for the rate of tropical forest loss, which has been consistently increasing since 1750. Aside from the 'Great Acceleration' indicators *sensu* (Steffen et al. 2015a), other indicators of change include the growth of invasive species (Vitousek et al. 1997), the homogenisation of the flora and fauna (Williams et al. 2015) and the increase in levels of extinction risk (Ceballos et al. 2015). The consistent pattern from these indicators is one of widespread global change as a result of human influence. With no sign that these trends will be reversed, an obvious next step is to establish the consequences of these changes with respect to the stability of earth systems and the ability to support Holocene-like conditions and sustain human societies.

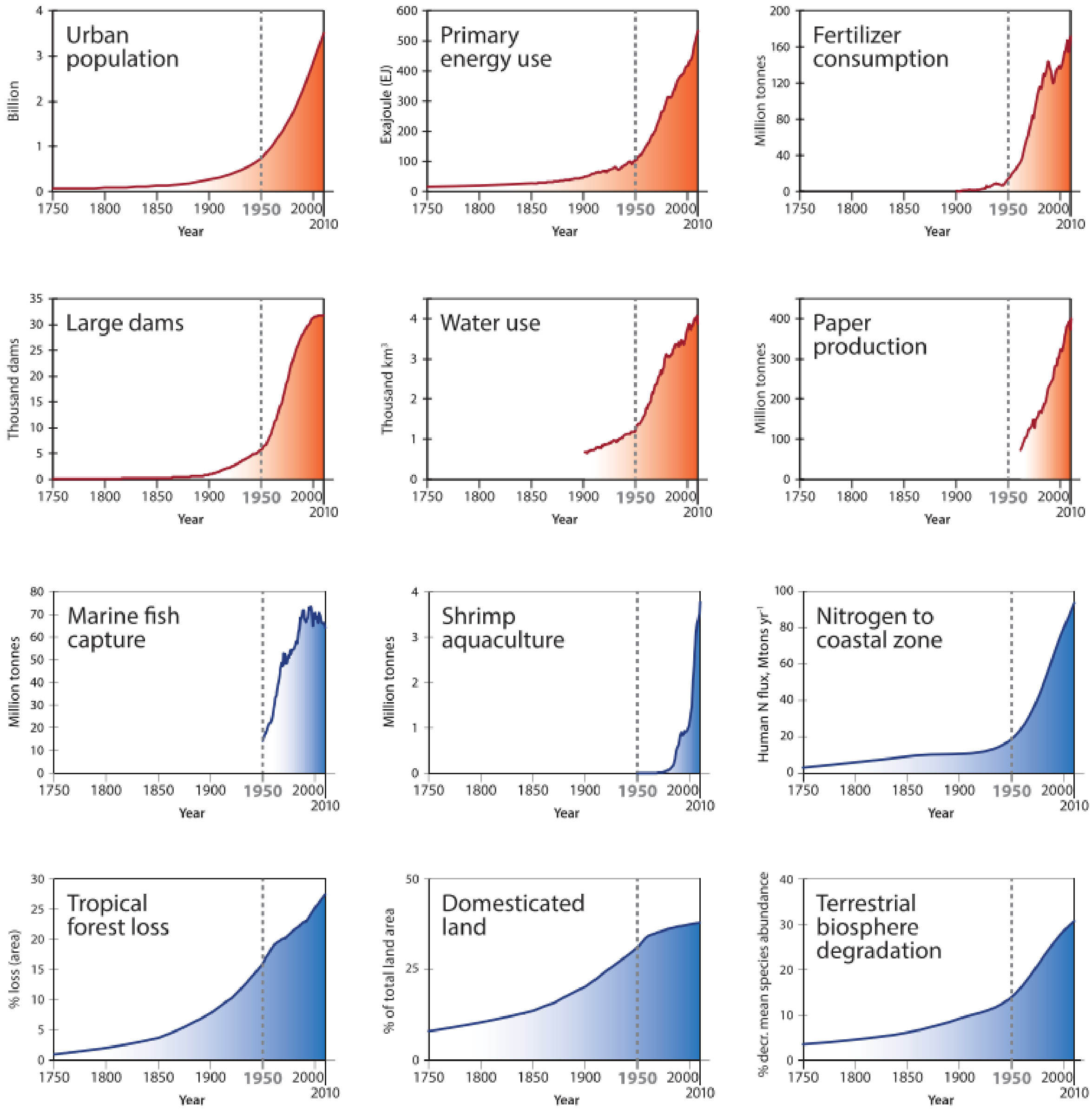


Figure 1. Selected examples of socio-economic (top six charts) and earth system (bottom six charts) indicators used to illustrate the 'Great Acceleration'. Source and full figure from: (Steffen et al. 2015a)

Significance of the Anthropocene for biodiversity and a stable planet

The Anthropocene is clearly characterised by pervasive and rapid changes to Earth's biotic and climatic systems, but is change necessarily always bad for the planet and for humanity? An apparent paradox is that, as environmental disruption increases, human well-being improves (Raudsepp-Hearne et al. 2010). The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005) noted that many (up to 60%) of the 'services' that humans rely on, whether they are provisioning (food, fuel), or regulating (climate, water), were declining, but human well-being, measured through indices like the human development index (HDI) were increasing (Raudsepp-Hearne et al. 2010). However, this finding depends on contextual factors such as how we quantify human well-being, which services are being considered and whether time-lags are important i.e. as services are depleted, growth in human well-being may eventually stall and decrease (Nelson 2011).

The Anthropocene has often been linked to increased loss of biodiversity, also referred to as the biodiversity crisis or the sixth mass extinction (Dirzo et al. 2014; Pimm et al. 2014; Ceballos et al. 2015). Anthropocene changes have also triggered responses that may not necessarily be considered 'bad' for biodiversity such as a reported increase in rates of speciation as a result of hybridisation (Thomas 2015), although this may be an artefact due to greater sampling effort from the Anthropocene compared to the geological past (Hulme et al. 2015). Similarly, ongoing disturbance to ecosystems through habitat transformation and the introduction of exotic species may lead to a change in species composition in some areas, but not necessarily a decline in species richness, as local extinctions are balanced out by invasions and richness may even increase in some areas (Ellis et al. 2012; Vellend et al. 2017). In contrast, negative consequences of ongoing Anthropocene changes have been linked to the health of earth systems, suggesting these systems will be pushed to a point that no longer supports human life (Steffen et al. 2015b). For example, the impact of human activities may reach a 'tipping-point', after which the planet shifts into an irreversible state that is undesirable and even inhospitable for human survival (Barnosky et al. 2012). It is argued that although a global state-shift is plausible, it is more likely that shifts will occur at localised or regional scales due to the lack of connectivity between systems and lack of homogeneity in the responses of different systems to change (Brook et al. 2013).

Even without a dramatic and rapid change in state, it is argued that there is a comfort zone for the Earth's biophysical systems, such as the climate, and the biosphere, within which we must remain in order to maintain Holocene-like conditions for humanity (Rockström et al. 2009; Steffen et al. 2015b). Pushing systems beyond a critical threshold, referred to as a 'planetary boundary', could destabilise the systems. However, this 'planetary boundary' framework has shortcomings because the control variables identified to measure processes, such as change in biosphere integrity, are hard to define and measure (Mace et al. 2014). In addition, inadequate data coverage on a global scale means we cannot describe a baseline against which to measure change (Steffen et al. 2015b). The Biodiversity Intactness Index (BII) (Scholes and Biggs 2005) has been adopted as a measure of whether we remain within the Biosphere integrity planetary boundary. The BII is a measure of the amount of natural biodiversity remaining in local ecosystems, and the precautionary boundary is met when BBI reduces by 10% (Steffen et al. 2015b), in other words, when less than 90% of natural biodiversity remains in local ecosystems. Recent application of the BBI on a global scale found that nearly 60% of the land surface is already beyond the precautionary boundary (Newbold et al. 2016). This suggests we are already compromising our ability to maintain a 'safe operating space', as defined by the planetary boundary framework.

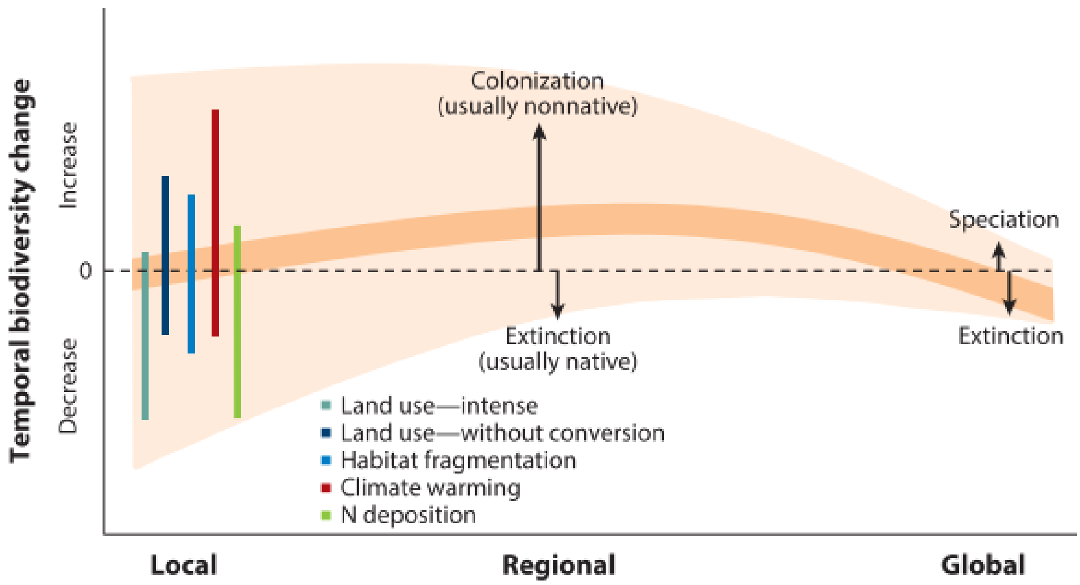


Figure 2. Illustration of Anthropocene biodiversity change from local to global scale based on a review of literature. The large shaded curve illustrates the range of plausible values and the smaller curve illustrates the central tendency. Coloured bars show local scale processes causing

increases or decreases in biodiversity with length of bar illustrating magnitude of effect. Source and full figure from (Vellend et al. 2017).

The planetary boundary framework is concerned mostly with global or biome scale dynamics, but consequences of biodiversity loss and biodiversity integrity can also be viewed at more regional or localised scales and by considering different facets of ecosystems such as their processes or functions. For example, plant diversity was found to have positive and negative responses to Anthropocene disturbance that were scale-dependent (Vellend et al. 2017) (Figure 2). Disturbances, and loss of particular species, may also have a disproportionate impact on ecosystem function compared to other species because of the functional traits they possess (Cardinale et al. 2012), or because of particular roles they play in ecosystems such as 'ecosystem engineers' (Barnosky et al. 2016). Other nuances in system response may reflect the different levels of resilience of an ecosystem i.e. its ability to recover from perturbations (Oliver et al. 2015).

In summary, a considerable literature has developed on the extent to which human-induced disturbances recorded in the Anthropocene are leading to the loss of biodiversity and accompanying losses of ecosystem function and services, and a reduced potential to maintain a healthy planet. There is evidence to suggest that loss of biodiversity is linked to reduction and loss of ecosystem services, and the magnitude of this effect could be as large as other major drivers of ecosystem change (Hooper et al. 2012; Cardinale et al. 2012; Isbell et al. 2017; Duffy et al. 2017; Huang et al. 2018). This is exemplified in a recent study that predicts irreversible ecosystem-scale changes based on simulations of biomass removal equivalent to the levels already experienced in contemporary ecosystems (Newbold et al. 2018).

Another major difference between the period of dominant influence by humans on ecosystems in the Holocene, and previous large-scale impacts by species on their environment, is that for the first time, we have been witness to, and have become aware of the dramatic changes that we have instigated. As far as we know we are the only species to be able to do this. Along with this awareness comes a sense of responsibility which is exemplified by the conservation movement, a group of individuals, organisations and ideas with the collective aim of protecting and conserving nature.

Responding to the Anthropocene biodiversity crisis -

i) conservation narratives

Long before the term 'Anthropocene' was coined, the importance of conserving biodiversity was acknowledged by early 20th century thinkers like Aldo Leopold and John Muir (Piccolo et al. 2018). Emphasising an eco-centric perspective, i.e. preserve nature for its own intrinsic value, they made the case for the protection of species and habitats in wild and pristine areas (Muir 1890; Leopold 1949). As human impact on biodiversity intensified throughout the 20th Century, the need to stem the loss of species and habitats by reducing the threats from humans, became the dominant focus of conservation – in other words protecting or preserving biodiversity despite the threats from people (Mace 2014). The Convention on Biological Diversity (CBD), adopted at the 1992 Rio de Janeiro 'Earth Summit', acknowledged the importance of both these narratives, noting the 'intrinsic value of biological diversity' and that 'biological diversity is being significantly reduced by human activities' (United Nations 1992).

The limited success of the CBD in reducing biodiversity loss or the threats to biodiversity led to the exploration of other strategies. A more anthropocentric view was adopted that acknowledged the fact that nature provides services that are useful to humans. These 'ecosystem services' could be commodified, thereby adding a value to nature (Costanza et al. 2014) and this idea gained broad attention after the publication of the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005). Although there is ongoing support for this narrative, there are also concerns that the monetisation of these services could actually lead to undervaluing nature (Silvertown 2015).

More recently, the developing narrative is for a more balanced approach to conservation that acknowledges nature and people and builds on the ideas of resilience and adaptation to the changes to which we are already committed (Mace 2014; Pearson 2016). Other recent narratives attempt to turn the often negative characteristics of conservation as a 'crisis discipline' (Soulé 1985) into something more optimistic by contemplating, for example, 'rewilding' ecosystems and embracing the idea of recovering systems and ultimately a recovering Earth (Balmford 2017; Jepson 2018). Narratives have been important in influencing the direction of conservation science and have also shaped the kinds of activities that conservationists undertake, and how biodiversity conservation is measured and monitored.

ii) conservation actions

Although there have been broad similarities in approaches to conservation practice, the different narratives described above have influenced the kinds of outcomes that conservationists strive to achieve (see Table 1). A simple model of a conservation intervention could be a conservationist gathering and analysing data and applying concepts from intersecting disciplines such as ecology, economics and geography to make decisions about what conservation actions are needed. They then seek to influence relevant sectors and apply for finance to support conservation activities or interventions. This model has been adapted as narratives change, for example, in the 'nature for itself' narrative, the data in this model would be species or areas and the theory would be on protected area coverage and placement (Table 1). The emphasis would then be on seeking to influence governments or agencies to support and enforce protection of the selected areas. Alternatively, an example of a 'nature despite people' activity is the development of agreements like the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which attempts to address the human-caused threat to wild species through trade in these species. Parties to the CBD can implement CITES by adopting domestic legislation to ensure that trade in a species does not threaten its survival in the wild (Secretariat of the CBD 1973).

Conservation actions today support all of the four conservation narratives previously highlighted (Mace 2014). For example 'wilderness' areas have recently been mapped on a global scale (Watson et al. 2016), which references many of the narratives, including the earliest 'nature for itself' conservation. Although conservation actions may change as further narratives are explored and developed, some techniques such as goal or target setting have been a feature of many of conservation narratives so far and are an important policy mechanism.

Table 1. Summary of different conservation narratives and examples of their associated conservation actions, based on Mace (2014).

Conservation Narrative (and alternative name or related themes)	Conservation Activity	References
Nature for itself (-1960+) (Eco-centric)	*Assessing:* • Species on Red List • % area protected • % 'Wilderness' areas	• (Mace 2014);(IUCN 2001; Vié et al. 2009) • (Secretariat of the Convention on

		Biological Diversity 2014) • (Watson et al. 2016)
Nature despite people (1980+) (Anthropogenic threats)	*Legislating:* CITES – Convention on International Trade in Endangered Species of Wild Fauna and Flora. *Target setting:* Convention on Biological Diversity (CBD)	 (Secretariat of the CBD 1973) (United Nations 1992)
Nature for people (2000+) (Natural capital) (Ecosystem services) (Resource Earth) (Anthro-centric) (New conservation)	*Accounting:* • Ecosystem services report UK • Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services	 • (UK National Ecosystem Assessment 2011) • (IPBES 2018)
People and nature (2010+) (Recoverable Earth) (Rewilding) (Conservation optimism)	*Sustaining, adapting and recovering:* Sustainable Development Goals (SDGs)	 (Pearson 2016) (Colloff et al. 2017)

iii) conservation targets

In recent years, targets, or time-bound goal setting, have become pervasive across many sectors, even our personal lives, and the conservation of biodiversity is no exception. Targets have been developed that cover all aspects of biodiversity conservation, operating at different scales, from the recovery of a single species (Akçakaya et al. 2018) to the global coverage of protected areas (Watson et al. 2014). High-profile conservation targets agreed through the CBD such as the 2010 Target (UNEP/CBD 2002) can be an effective mechanism to stimulate and co-ordinate conservation action because parties to the convention are publicly committed to achieving these targets. However, targets can also appear to be 'toothless' in the sense that they are typically non-binding and there are limited repercussions if targets are not met (Heywood 2017). For example, by most indicators, the CBD 2010 Target was not met; worse still, by some indicators, the trend of loss actually increased (Butchart et al. 2010). In response, in 2010, parties to the CBD simply agreed on a revised vision, and a new set of 20 strategic targets were adopted (UNEP/CBD 2010a). Goal setting can also be compromised because competing, often political, interests can influence scientific integrity and ambition of targets (Doherty et al. 2018). Goals can also be poorly defined, leading to ambiguities (Tear et al. 2005), and uncertainty as to when goals have actually been met (Butchart et al. 2016).

When targets have been clearly defined, and when the roles of stakeholders are clearly identified, it is possible for global conservation targets to be met. For example, the first target of the Global Strategy for Plant Conservation (GSPC) was to deliver by 2010 a "…*widely accessible working list of known plant species, as a step towards a complete world flora*." (UNEP/CBD 2002). The successful publication of The Plant List in 2010 (http://www.theplantlist.org) (The Plant List 2013) depended on the business-as-usual activities of taxonomists around the world, describing and revising plant taxa, in addition to a coordinated effort by the Royal Botanic Gardens, Kew, and the Missouri Botanical Gardens as lead institutions to pull together the final result (Paton and Lughadha 2011). Successful delivery of a target then opens up the opportunity to deliver a more ambitious target for the next round, as was the case with the updated GSPC targets that now seeks to achieve the more comprehensive and ambitious goal of "*An online flora of all known plants*." (UNEP/CBD 2010b). Successful delivery of targets can also be enabling. For example, the current GSPC Target 2 aims for "*An assessment of the conservation status of all known plant species, as far as possible, to guide conservation action*." (UNEP/CBD 2010b) and this can now be measured against the baseline of names for all known plant species provided by The Plant List.

Targets can also stimulate co-benefits that operate beyond the simple binary response of success or failure for each target (Doherty et al. 2018). For example, the setting of the CBD 2010 Target triggered the development of new, and refinement of existing, indicators (Stuart and Collen 2013). For example, in response to the 2010 Target, the Red List Index was proposed (Butchart et al. 2004; Butchart et al. 2005), and refined (Butchart et al. 2007), as an indicator for the sub-target on 'change in status of threatened species'. The methodology was later adapted to account for under-represented clades of biodiversity through a sample approach (Baillie et al. 2008), and has also been used to assess impact of conservation organisations (Young et al. 2014). Other co-benefits of target setting include raising awareness about the importance of biodiversity (Stuart and Collen 2013; Doherty et al. 2018) and galvanising activity in the conservation community (Williams et al. 2012).

Targets like the CBD 2010 Target and the Aichi 2020 Targets adopt a broad definition of biodiversity, but the data available for indicators are often lacking for parts of biodiversity that are less well-known (Cardoso et al. 2011). This bias is evident in biodiversity research (Troudet et al. 2017) and conservation research (Di Marco et al. 2017), but it is the bias in data availability that is most likely to impact the patterns that emerge from global indicators (Meyer et al. 2016; Troudet et al. 2017). Although the better known groups have been shown to be good surrogates for biodiversity as a whole, at least in some situations (Rodrigues and Brooks 2007; Grantham et al. 2010), the addition of data on other groups can improve effectiveness of conservation prioritisation by highlighting different priority areas (Clausnitzer et al. 2009; Larsen et al. 2012). Addressing these biodiversity gaps will help achieve more representative indicators and more robust responses to global biodiversity targets.

In summary, as biodiversity continues to decline, there is likely to be an important role for conservation targets and associated indicators if the vision of the CBD is to be realised (Mace et al. 2018). However, any future targets should adhere to the principles of smart target setting that includes being specific, measurable, unambiguous and credible (Tear et al. 2005; Butchart et al. 2016) and should strive for better representativeness of the lesser known components of biodiversity.

iv) Species conservation status and indicators for global conservation targets

One consistent component of global biodiversity targets has been the use species conservation status assessments (Figure 3). The term ‘conservation status’ is ambiguous and may refer to a qualitative statement on the extinction risk a species may be facing (Mancina et al. 2007), whether the species has been conserved in genebanks (Brehm et al. 2010), or whether suitable habitat is available to support viable populations of a species e.g. in the European Union species and habitats directive (Council of European Communities 1992). Another type of conservation status assessment is a quantitative evaluation of the likelihood of species extinction such as the approach provided by the IUCN Red List of Threatened Species [hereafter Red List] system of categories and criteria (IUCN 2012).

Conservation status assessments have been incorporated into many global conservation targets (Figure 3) such as the CBD Aichi Target 12 ‘… *the extinction of known threatened species has been prevented*…’ (UNEP/CBD 2010). Target 12 explicitly identifies extinction risk and ‘threatened’ species, so responses to this target could be drawn from data on the Red List. The Sustainable

Development Goals (SDGs) (United Nations 2017) also incorporate conservation assessments in response to Target 15 – Life on the Land, explicitly using the Red List Index (Butchart et al. 2007) to measure changes in species' extinction risk (United Nations Department of Economic and Social Affairs (UN DESA) 2018).

Conservation status assessments can also be defined by strict or generic definitions and can be applied at both regional and global scales. For example, an open definition of conservation status was used for Target 2 of the Global Strategy for Plant Conservation, which calls for an '…*assessment of the conservation status of all known plant species*…' (CBD 2010). Assessment systems have also been developed at sub-global scale, such as the modified Red List system used by the New Zealand Department of Conservation to rank species conservation status in New Zealand (Hitchmough et al. 2008).

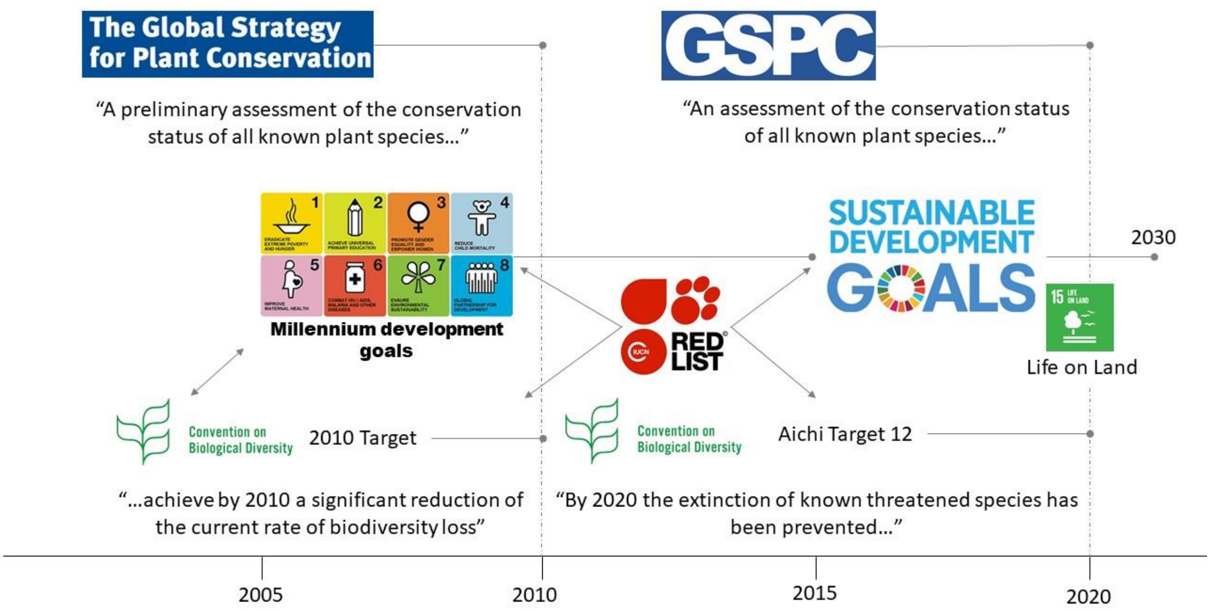


Figure 3. Examples of conservation targets that have incorporated species level conservation status assessments. The GSPC target does not specify an assessment system. The Millennium Development Goals (MDGs) adopted the CBD 2010 Biodiversity Target, which used the IUCN Red List Index to measure change in status of threatened species. The MDGs were superseded by the Sustainable Development Goals (SDGs). Both the SDGs (Target 15: Life on Land) and Aichi Biodiversity Target 12 report on status of threatened species using the IUCN Red List Index

The ubiquity of conservation status assessments at the species level may in part be due to the utility of species as an operational unit for conservation. Assessments at the species level can be easily compared across regions and between higher taxonomic groups. Species can also have resonance with the public who increasingly recognise that the global loss of a single species in the wild is currently irreversible (but note that genetic banks have preserved material for many species already extinct in the wild in the hope that restoration or resurrection may one day be possible (Shapiro 2017; O'Donnell and Sharrock 2017). Conservationists recognise the importance of species as unique representations of genes and features (Humphries et al. 1995), whose utility may not currently be known. Loss of species therefore reduces options for utilisation of biodiversity for current and future conditions (Woodcock and Hayward 2016).

Conservation status assessments have also remained in common use because they have been widely utilised in conservation prioritisation (Brehm et al. 2010; Arponen 2012). However, it is important to note that using species conservation status alone may not be appropriate for conservation prioritisation as other biodiversity features such as rarity, endemism, functional traits or evolutionary distinctness may be the objective for protection (Possingham et al. 2002; Lamoreux et al. 2003), and costs and benefits of interventions and likelihood of success also need to be considered (Marsh et al. 2007; McCarthy et al. 2008). Extinction risk incorporates two concepts in conservation planning – threats and sensitivity to threats (Kukkala and Moilanen 2013). If we relied simply on magnitude of threats to an area as the reason for allocating conservation funds, it would be misplaced if the species in the area were robust to these threats. The added value of conservation status assessments, in particular those that incorporate extinction risk, is that they provide the dimension of time; in other words, they tell us the urgency with which we need to act to avoid extinction (Martin et al. 2012). Temporal accuracy of extinction estimates is likely to be low, as predicting exact time of extinction is difficult (Cronk 2016), but if a consistent species conservation assessment system is used, species can be compared and ranked, which can be part of a systematic conservation planning approach.

v) Extinction risk assessments

One specific type of conservation status assessment is the estimation of species extinction risk. To understand extinction risk we need to first understand extinction. A species is extinct when the last individual of that species has died – a fate that has befallen most species that have ever existed (Raup 1994). Although extinction is difficult to confirm because it relies on evidence of non-detection, the probability of extinction can be estimated using data on time series of species records or occurrences (Boakes et al. 2015; Thompson et al. 2017) or qualitative evidence approaches (Keith et al. 2017), or both (Butchart et al. 2018). Although recent extinctions have been documented (e.g. Bruegmann et al. 2016), they may be under-reported by scientists because falsely declaring a species extinct, the 'Romeo Error' (Collar, 1998), can cause loss of public confidence in conservation science and simultaneously can divert conservation resources from a species in most urgent need of attention (Brook and Alroy, 2017).

Although it is important to declare whether a species is either extinct or extant, it is more informative for conservationists who wish to make proactive decisions to know the trajectory of a species towards extinction – its risk or probability of extinction. Extinction theory stems from demographic studies that established that declining populations were at greater extinction risk and that small populations were susceptible to extinction due to stochasticity, and genetic (Allee) effects (Mace and Lande 1991; Courchamp et al. 1999). Extinction risk theory was further developed with the concept of the minimum viable population (MVP), which defines the smallest population required for a species to remain extant in the foreseeable future, and therefore robust to extinction (Shaffer 1981). However, a review of the literature covering 30 years of published estimates of MVP revealed that MVP had only been estimated for 212 species (Traill et al. 2007). Efforts to generalise MVP to a single value (Traill et al. 2010) may not be appropriate as extinction risk is dependent on other factors such as life histories, habitat quality and current threats (Flather et al. 2011). Lack of time and resources to estimate MVP for all species is therefore a limiting factor in use of MVP for extinction risk estimation for conservationists.

In response to these data limitations, a comparative approach has been applied to find correlates of extinction risk, so that extinction risk of un-assessed species can be estimated (Fisher and Owens 2004). Intrinsic variables such as biological characteristics, or traits, and geographic range size have been found to be good predictors of extinction risk (Cardillo et al. 2005; Marco et al. 2014), as have external variables such as anthropogenic threats (Davies et al. 2006; Peters et al. 2015). Arguably these are pro-active approaches to conservation, aiming to highlight species that could be facing extinction, but are not currently assessed, or need to be reassessed. However, the results of such studies may not be directly influencing conservation practice (Cardillo and Meijaard 2012). For example, life history, geographic and threat predictors were used to estimate likely extinction risk (threatened or not threatened) for mammals listed as Data Deficient on the IUCN Red List (Bland et al. 2015). The 313 species predicted to be threatened may be considered priorities for formal assessment on the IUCN Red List, but as of the latest Red List update (ref 2018-2) >80% remain with Data Deficient status, although this may partly be due to a lag in time taken to publish on the IUCN Red List.

Comparative studies of extinction risk often rely on a single data source to train and validate models of extinction risk – the IUCN Red List of Threatened Species (IUCN 2001). The Red List has become the *de facto* global standard for extinction risk assessments and provides the most comprehensive coverage of extinction risk status (Rodrigues et al. 2006). The Red List criteria (IUCN 2012) have developed in response to criticism of subjectivity and inconsistency in application (Mace and Lande 1991) to become an evidence-based system that measures the symptoms of extinction risk and allows for uncertainty and inference (Mace et al. 2008). The Red List has been used to map global-scale patterns of extinction risk (Grenyer et al. 2006; Boyd et al. 2008), and inform decision making for business (Bennun et al. 2018), has been incorporated into initiatives aiming to prevent imminent extinctions (Ricketts et al. 2005) and, as already mentioned above, has become an integral component of indicators used to report on global biodiversity targets (Figure 3).

Despite efforts to make the Red List criteria quantitative and robust (Mace et al. 2008), the practical application of the criteria to different groups has revealed some shortcomings, including variation in interpretation of guidelines by assessors (Hayward et al. 2015). One criterion that has received attention in the literature, is in fact the most widely applied criterion, B (Collen et al. 2016), which deals with the geographic range of a species. Two measures are used to determine range: extent of occurrence (EOO) and area of occupancy (AOO), based on pioneering work of Gaston (Gaston 1994; Gaston 2003). The EOO, which measures the degree to which risk is spread across the occurrences of a species (Gaston and Fuller 2009), was found to be applied inconsistently across assessment groups mainly due to uncertainty about whether 'discontinuities or disjunctions', as reported in the Red List criteria (IUCN 2012), should be excluded from the calculation of EOO or not. Plant assessors generally preferred to calculate EOO based on a set of georeferenced occurrences by drawing a convex hull or minimum convex polygon (MCP) around the occurrences, thereby including discontinuities, and they developed tools to automate this calculation (Willis et al. 2003; Bachman et al. 2011). Other Red List assessment approaches used in bird and mammal assessments tended to use polygon maps and the sum of areas of polygons as the EOO value, thereby excluding discontinuities. The idiosyncratic nature in the way discontinuities were being removed led to the adoption of the MCP approach to ensure consistent and comparable measurement of EOO (Joppa et al. 2016).

Similarly, the calculation of area of occupancy (AOO) has proven problematic. To ensure consistency and comparability across taxa, IUCN guidelines suggest AOO should be measured at the reference scale of with 2 km by 2 km cells (4 km squared) (IUCN Standards And Petitions Subcommittee 2014). However, occurrence data are rarely recorded at this scale and under-sampling will lead to underestimates of AOO (Gaston and Fuller 2009). Methods to 'downscale' have been developed that allow coarse scale occupancy to be downscaled to finer scales, such as the IUCN reference scale (Marsh et al. 2018). Other problems with AOO estimation stem from the underlying grid that is used to determine occupancy. Occupancy is usually defined as the number of occupied cells multiplied by the area of a cell (IUCN Standards And Petitions Subcommittee 2014). Even using a standard reference scale, AOO values can differ due to origin and rotation of the grid being used to measure AOO. Techniques have been developed that attempt to optimise grid origin and rotation to achieve a minimum AOO that can reduce AOO by 40%, compared to commonly applied algorithms (Moat et al. 2018), or avoid bias from grids by using circular buffers (Breiner and Bergamini 2018)

Estimation of EOO and AOO are further hampered by temporal and spatial bias in occurrence data (Daru et al. 2018) as well as problems of under-sampling (Gaston and Fuller 2008; IUCN Standards And Petitions Subcommittee 2014). One approach to overcome these issues is to use species distribution models (SDM) (Maycock et al. 2012; Fivaz and Gonseth 2014; Syfert et al. 2014). Distribution models typically correlate primary occurrence data and environmental variables to produce a model of the suitable environmental space for a species. The model can then be applied to identify similar environmental space in other areas, and therefore to predict the potential presence of the modelled species. Predicted occurrence can then be used to fill gaps and therefore reduce omission errors in EOO and AOO estimations derived from occurrence data alone (Rondinini et al. 2006). However, care must be taken not to assume high prediction probabilities equate to presence of a species as other factors not considered in the modelling process could influence occurrence, such as competition and dispersal ability.

Aside from the challenges of consistently applying the Red List criteria, issues have been raised regarding the emphasis that the Red List gives to species with small geographic ranges and small populations (Gaston and Fuller 2008; Peters et al. 2015). Abundant and wide-ranging species provide a considerable contribution to biomass such that even small proportional losses, i.e. less than would qualify for a Red List threatened category, can have a large effect on ecosystem stability and should be an important consideration for conservation (Gaston and Fuller 2008; Lindenmayer et al. 2011; Baker et al. 2018).

Despite its renown and utility (Vié et al. 2009), the Red List remains incomplete and most known species have not been assessed and published on the Red List. Furthermore, the species that have been published on the Red List, are biased towards the better-known taxonomic groups. Although the Red List criteria are designed to enable assessment of species across the taxonomic spectrum, excluding micro-organisms (IUCN Standards And Petitions Subcommittee 2014), the majority of assessments have been of vertebrate species (IUCN 2017). This may be due to specific challenges in applying the criteria for certain groups e.g. fungi (Dahlberg and Mueller 2011). If the complete Red List were used to determine the proportion of species threatened with extinction it would provide a misleading answer. The Red List summary statistics draw attention to this issue and note that: *Where <80% of species within a group have been evaluated, figures for % threatened species are not provided because there is insufficient coverage for these groups. It is only possible to provide reliable figures for % threatened species for those groups that are completely or almost completely evaluated*. (IUCN 2017). The result is that of all invertebrate, plant, fungi and protist groups (representing > 1.5 million known species), only two groups, Gymnosperms (n = 1,052 species) and horseshoe crabs (n = 4 species) are sufficiently assessed to report overall proportion threatened (IUCN 2017).

Does the lack of coverage on the Red List matter? If we simply need to respond to a target such as Aichi 2020 Target 12, we can achieve broad coverage of biodiversity using comprehensively assessed groups and supplement these with the sampled approach of the Red List Index for non-comprehensively assessed groups (Baillie et al. 2008; Collen and Baillie 2010). If we wish to inform conservation priorities, we know that assessing more groups adds new information to patterns of extinction risk (Clausnitzer et al. 2009). We know that important constituents of biodiversity are missing from the Red List, such as plants, which account for 80% of global biomass (Bar-On et al. 2018), and invertebrates, which account for 80% of all known species (Cardoso et al. 2011). It is likely that many of these species already provide vital ecosystem services, even if these services have not been elucidated yet, and it would therefore be prudent to preserve options for current and future uses of these species (Gascon et al. 2015). This suggests coverage does matter if the Red List is to provide a truly comprehensive tool to support conservation.

The taxonomic gaps in the Red List are already acknowledged and identified as a priority to address (Rodrigues et al. 2006; Stuart et al. 2010), although it has been argued that the estimated cost to grow the Red List into a more comprehensive Barometer of Life (USD 60 million) could be better used for on-the-ground conservation (Bridgewater 2016). Other challenges to growing the Red List include the need to keep the dataset up-to-date (Rondinini et al. 2013). Focusing efforts on assessing more species means that there will be a growing pool of species that require reassessments and resources will need to be shared to cover both aspects, expansion and temporal continuity. Unless methods are developed to scale-up the production of high quality and timely assessments, or resources can be found for long term support, the ambitions of the Red List may not be met.

In summary, assessing extinction is data-intensive and lack of resources for conservation limit the number of species that can be assessed. However, assessing extinction *risk* can be achieved with surrogates of extinction and is a more pro-active approach. Extinction risk assessment at the global scale is dominated by the IUCN, which provides the criteria, infrastructure and network to support its flagship product, the Red List of Threatened Species. If the Red List is to maintain its role, it needs to provide breadth (representativeness – global indicators) and depth (high quality assessments to support conservation) and temporal continuity (to support indicators of change in extinction risk). Inconsistencies in application of the Red List criteria have been identified and attempts have been made to address them, but efforts should continue so that methods can be refined, especially for groups currently under-represented on the Red List.

vi) Gaps in conservation assessment indicators for plants

Mace et al. (2018) acknowledged that indicators may need better representativeness and data coverage if they are to support conservation goals. The kingdom of plants represents one of these gaps, although plants are an exceptional case because not only are they implicitly included in global biodiversity indicators, but they also have their own global strategy, the Global Strategy for Plant Conservation (GSPC), that includes plant-specific targets (Wyse Jackson and Kennedy 2009). Target 2 of the GSPC calls for a "…*An assessment of the conservation status of all known plant species, as far as possible, to guide conservation action*.". Despite calls to arms (Schatz, 2009) and regional progress (Raimondo, von Staden and Donaldson, 2013), an indicator has not been defined and there is no clear picture of global progress against this target (Sharrock et al. 2014). Progress in assessing conservation status of plants, especially determining which species are threatened, will not only address Target 2, but will help provide a quantitative response to other targets in the strategy that rely on conservation status such as target 7: *At least 75 per cent of known threatened plant species conserved in situ* and target 8: *At least 75 per cent of threatened plant species in ex situ collections…* (UNEP/CBD 2010b).

Conclusion

Human activity has for a long time been associated with disturbance and modification of earth systems such as the biosphere, and its associated biological diversity or biodiversity. However, the rate of change, both in terms of human impact and loss of biodiversity, has accelerated in the last 50 years, to the extent that we risk disrupting the services that we depend on for our own survival. Humans are uniquely placed in history as being a species that is not only a dominant force on the earth but is also aware of the impact of its actions, and is also unique in that it can do something to address this it.

Conservation of biodiversity encapsulates this desire to respond to biodiversity loss and conservationists have been driven by different narratives that highlight different aspects and approaches to conservation. Targets have been a useful approach to galvanise the conservation community into collective action, to stimulate research and methodological developments and to raise awareness of the importance of biodiversity.

The assessment of a species' conservation status has been one of the approaches employed to determine threats to a species, often in the form of the probability of extinction risk, although it may also include recommendations on the actions needed to conserve a species. These assessments have proven useful to guide conservation prioritisation or triage, to leverage conservation funding and to offset or even halt threats.

Another important application of conservation assessments is in global indicators that are used to monitor biodiversity. However, gaps in data coverage expose limitations in these indicators, such as lack of taxonomic representativeness, especially for important components of biodiversity such as plants. Attaining greater coverage of conservation assessments for groups like plants helps to address gaps in global, as well as plant-specific, indicators. This aim is challenging as large numbers of species need to be assessed (more than any that have been assessed to date) in a timely manner, without compromising accuracy. If this can be achieved, decision makers and policy makers will be better informed when planning conservation interventions. Ultimately, whichever attribute of a species makes it a priority for conservation - its functional role, phylogenetic distinctness, rarity or cultural importance - we need to know if it has a viable population or is bound for extinction, because we currently do not have the technological capability to restore species that become extinct.

ii) Research questions and objectives

The fundamental aim of this thesis is to gain a more quantitative answer to the question: 'How threatened are plants?' Answering this question responds directly to several global biodiversity and conservation targets. However, in order to generate appropriate objectives, the parameters of the question need to be more fully defined.

In terms of biological scale, the focus is at the species level as this is most commonly used for conservation, although progress has been made in categorising threats to ecosystems where ecosystem collapse is viewed as analogous to species extinction (Keith et al. 2013). In terms of temporal scale, the focus is on contemporary threat status, not historical threats and mass-extinction events. The aim is to use knowledge of present-day plant threat status to inform present-day conservation. In terms of taxonomic scale, the focus is on land plants, including the major plant groups the Gymnosperms, Angiosperms and Ferns, as well as Lycopods (club mosses) and Bryophytes, but not including Algae (Figure 4). With these parameters in mind, a more precise question is: 'What is the contemporary level of threat to land plant species?'

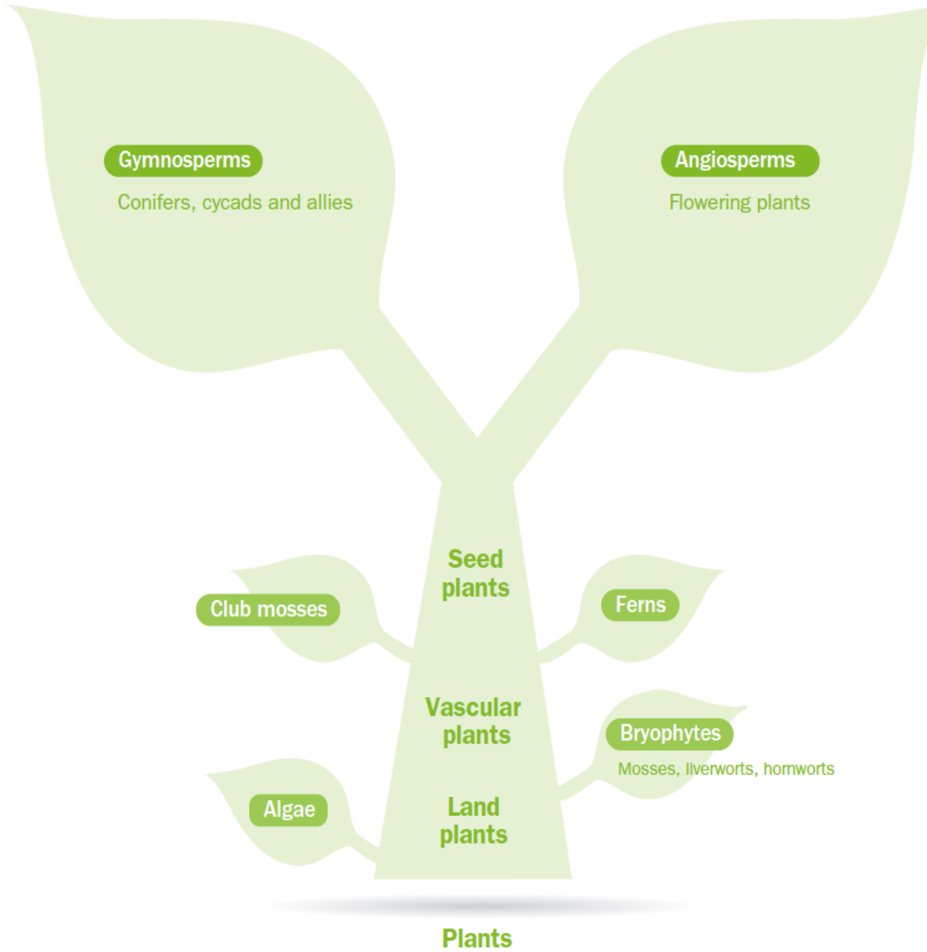


Figure 4

Schematic diagram of the major plant groups and their relationships. Groups at the base of the tree are the oldest. Algae are out of the scope of this thesis. Phylogeny based on APG IV, first published in the State of the World's Plants report 2016 (RBG Kew 2016), reproduced with permission from the Board of Trustees of the Royal Botanic Gardens, Kew.

Research questions

From the starting question of 'What is the contemporary level of threat to land plant species?' a series of additional framing questions can then be asked to further refine the overall aim of this thesis, including 'How many species have been assessed?' and 'What proportion of plants are at risk of extinction?' (Figure 5).

Research objectives

In response to these framing questions I set out five key objectives (below) and illustrate how these objectives relate to the framing questions (Figure 5).

1. Provide a quantitative baseline estimate for the percentage of plant species that are threatened with extinction
2. Establish a global indicator of plant extinction risk that can be used to report on global policy targets such as Aichi Biodiversity Target 12, GSPC Target 2 and Sustainable Development Goals Target 15
3. Establish a working list of plant threat assessments and a subset list of 'threatened' plants to inform GSPC target 2 and to support other associated GSPC targets.
4. Using plants as a case study, review recent progress, ongoing challenges and opportunities for Red List assessment.
5. Assess extinction risk status and threats to *Aloe* occurring in the Horn of Africa, review conservation gaps for *Aloe* in this region and identify priorities for increased protection.

Figure 5

Summary of objectives and how they link to framing questions.

iii) Methods and critical review

The outputs of this thesis are the culmination of many years' work, in collaboration with many individuals. The detailed methodologies are outlined in each paper (see section B. The published and un-published papers). In the following section I outline some of the commonalities in the methods applied in the papers and review some of the caveats.

The role of specimens

Despite a wealth of literature on the diversity and distribution of plants, many plant species are not known in much more detail than the formal species description and at least one cited voucher specimen (a specimen is an annotated collection of plant material, usually flowering or fruiting, that has been dried and pressed in order to preserve it) (Nic Lughadha et al. 2005; Brummitt et al. 2008). Voucher specimens are also annotated, usually describing the location and date of collection, the name of the collector and a suggested identification, as well as other various data depending on the collector. These data, when digitised and georeferenced (the process of adding an x y coordinate to a location description) can be mapped and put into the context of contemporary or historical spatial data such as land cover. The spatial distribution of a species is one variable that can help assess the category of extinction risk and was introduced to the Red List criteria precisely because plants often lacked other relevant data for assessing extinction risk such as population size and rates of decline (Mace et al. 2008; IUCN Red List 2012). Specimens underpin the plant Red List assessment methodology that has been employed in two papers included in this thesis - see **Paper 1 (Green Plants in the Red)** and **Paper 4 (Extinction Risk – Horn of Africa Aloes)**. The 'desktop' methodology, which includes mapping specimens, as well as running additional GIS analysis, literature research and consultation of taxonomic or regional experts (Brummitt et al. 2008) was employed in **Paper 1 (Green Plants in the Red)** to assess a random sample of plant species. The resulting Red List ratings were then combined to get an overview of extinction risk in plants and to establish a baseline index of plant extinction risk from which future measurements could be made. The 'desktop' methodology was also applied to all species of Aloe in the Horn of Africa, prior to additional analysis to identify priority sites for protected area expansion for *Aloe* – see **Paper 4 (Extinction Risk – Horn of Africa Aloes)**.

Literature search

A different approach was adopted to respond to the challenge of creating a working list of conservation assessments and a subset of threatened species - see **Paper 2 (GSPC Target 2)**.

Rather than generating new Red List assessments, a literature search was carried out to pull together the existing assessments. The inclusive nature of the GSPC target 'An assessment of the conservation status of all known plant species, as far as possible, to guide conservation action' (UNEP/CBD 2010b) meant that other assessment systems, not just the IUCN Red List, could be used. The literature was trawled for any digitally accessible assessments and these data were subject to three data cleaning steps before the final list could be generated: firstly, matching plant names to a taxonomic name backbone, summarising threat status to a consistent set of values and grouping assessments by geographic scale. The summary of threat status facilitated the generation of a 'threatened' subset of species, an important milestone for GSPC target 2 and a contribution to other targets.

Personal experience

Finally, I used a more reflective approach to assess the current issues surrounding the production and publication of plant extinction risk assessments. I drew on several years of experience compiling and submitting Red List assessments as well as my experience training others, working on Red List projects and talking to collaborators directly involved in Red List assessments, to establish the recent changes, progress, ongoing challenges and opportunities for Red Listing, with a focus on plants. These views are consolidated into a 'perspectives' article see - **Paper 3 (Red List Challenges)** and are aimed at drawing attention to ongoing barriers, highlighting and celebrating successes where they have occurred and proposing solutions to problems so that plant Red Listing can push forward and support a step-change in plant conservation.

Critical review of methods

In this section I provide a critical analysis of the methods employed during the research for each paper.

Paper 1 (Green Plants in the Red)

This paper was born out of a collaborative project developed specifically in response to the Convention on Biological Diversity Biodiversity target (Balmford et al. 2005). As the IUCN Red List Categories and Criteria had been chosen as the mechanism to estimate status and trends in threatened species, limited discussion was provided on the strengths and weaknesses of the IUCN system, especially, the limitations in using specimen data to underpin these assessments. My literature review above (section Ai) attempts to addresses this problem, but further discussion would have helped to put the Red List methodology into the broader the context of extinction risk science.

A limitation of the analysis was the substitution of the eudicot clade with the legume family, which was because there is no authoritative eudicot checklist. Legumes were selected as a surrogate because they have been shown to reflect angiosperm diversity patterns at the generic level better than any other family (Nic Lughadha et al. 2005). The cosmopolitan distribution, and broad ecological representation warrants the use of legumes as a substitute, but when a full eudicot checklist becomes available, the legume sample should be replaced with a sample drawn from the full eudicot list.

All scientific research should be well documented so that methods can be replicated to check validity of results. **Paper 1 (Green Plants in the Red)** could have described the methodological approach more clearly, for example, by separating out the methods of sampling species from the methods for assessing species using the IUCN Red List categories and criteria. Throughout the course of this PhD I have developed programming skills in R statistical language (R Core Team 2016). For the latter two papers included in this thesis **Paper 3 (Red List Challenges)** and **Paper 4 (Extinction Risk – Horn of Africa Aloes)** I was able to document methods in code that is published in an open-source repository so that results can be more readily replicated. I will endeavour to follow this approach for future research articles.

Paper 2 (GSPC Target 2)

The second paper in this thesis specifically responds to the second target in the Global Strategy for Plant Conservation (CBD 2010). This is primarily a status assessment; future work could develop from this baseline dataset for research questions such as how is conservation assessment effort distributed across the globe and how has this changed over time? A gap analysis could also be generated that seeks to identify the regions or countries with the greatest gaps in assessment coverage and could analyse the reasons for these gaps e.g. access to botanical information, economic prosperity or corruption levels and could prioritise assessments in the most threatened areas.

Paper 3 (Red List Challenges)

This paper is a 'perspectives' manuscript that reviews recent changes and developments in the conservation assessment of species using the IUCN Red List methodology. It assumes knowledge of the IUCN Red List and assessment methodology and does not critically evaluate strengths and weaknesses of the Red List approach. A more thorough overview of conservation assessments and the IUCN Red List approach has been provided in the literature review above (section Ai).

In previous versions of this paper I highlighted changes to the Red List methodology that were designed to remove a barrier to Red Listing production or to incentivise assessment production. However, it was not clear to what extent, or even whether, these changes impacted the Red List. To evaluate the success of these changes I summarised the plant Red List dataset and separated different facets of the assessments, such as the assessment language, and generated a dashboard to display this information (Figure 6). For some issues, we can see that changes to rules, such as removing the requirement to document assessments in English (Spanish, French and Portuguese are now allowed), have made little difference, with only a small number of assessments published using non-English languages so far. Future work can now explore the reasons why this has occurred – are assessors not aware that different languages can be used or are there concerns that assessments in non-English languages will not be reviewed? In contrast, other issues are still hard to evaluate, such as the impact of training on the growth of the Red List. Training is inadequately documented, and it is difficult to determine whether more training is leading to a growth in active assessors. Disambiguation of names using services like ORCID (https://orcid.org) may help to resolve these issues and allow more thorough investigation of the impact of training on Red List assessment.

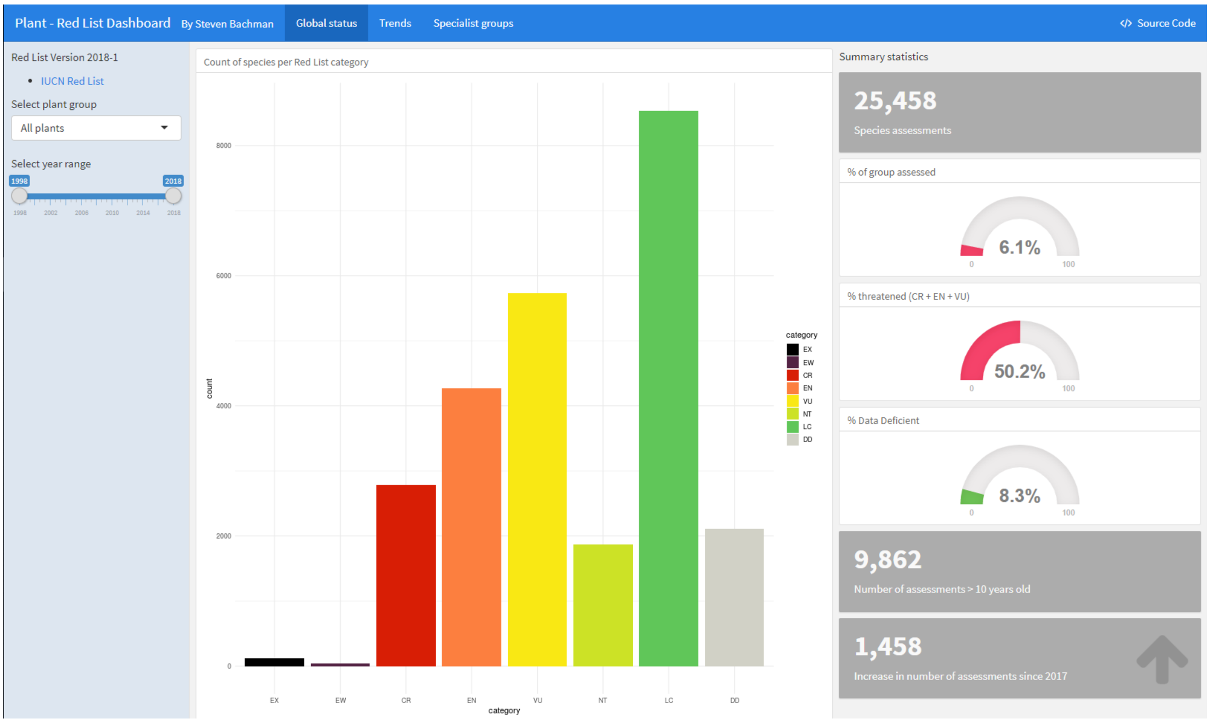


Figure 6

Screenshot of a shiny dashboard I developed to accompany **Paper 3 (Red List Challenges)** that summarises the plant Red List assessment data so that status and trends can be monitored. It will be updated whenever the IUCN Red List is updated. https://spbachman.shinyapps.io/plantdash

In this paper, we highlight how the combination of reduced data requirements for assessments and a batch import facility open the possibility to substantially scale up the publication of non-threatened species – threatened species still require a high level of documentation to support the assessments. The paper notes that predictive models can be used to identify non-threatened species (Darrah et al. 2017) and future work should extend this approach to all plants. However, an important consideration is the accuracy with which models can predict threatened and non-threatened species. A potentially threatened species that was predicted to be non-threatened could miss important conservation attention, while the alternative error (predicting a non-threatened species to be threatened) could allocate precious conservation resource to a species that doesn't need it. The IUCN assessment procedure mitigates these risks to some extent through a peer-review system that should identify misclassifications, but this also adds a resource cost to the reviewer network. Further work is needed to look at the trade-offs in efficiency and errors with this approach in order to find an optimal solution.

Paper 4 (Horn of Africa Aloes)

Papers 1–3 demonstrate the creation of new knowledge: producing an estimate of threat levels for plants (Paper 1), providing an estimate of progress in conservation assessment generation against a global conservation target (Paper 2), and reviewing current knowledge to indicate how progress can be made (Paper 3). My final paper in this thesis (Paper 4) balances those more generalised assessments with a specific case study. It addresses the research questions: 'What are the current levels of extinction risk, threat and conservation coverage for the genus *Aloe* in the Horn of Africa? How can this coverage be extended to fill conservation gaps in the most efficient manner?'

When assessing extinction risk, the best available data for plants are often geographic range data, as information on population size, or declines in populations is rarely available. Geographic ranges can be estimated using herbarium specimens or observation, although these data are opportunistic and therefore are often biased. Also, where survey effort is low, it may lead to omission errors and fail to detect the presence of a species. This could be mitigated to some extent by developing distribution models that predict presence of a species where conditions appear to be suitable. However, when numbers of unique occurrences per species are very low, or where a species is only known form a single site, modelling techniques cannot be applied as there are insufficient data to train and test the model. Estimation of extinction risk using the IUCN criteria allows for uncertainty, and occurrence data can be supplemented with expert knowledge so that minimum and maximum estimates of geographic extent can be made. Although expert opinion is subjective and may not be verifiable in the same way that herbarium voucher specimens can, it is still useful information. If uncertainty is within the bounds of the geographic range limits of a threat category, then it is appropriate to assess a species in that category, and note the uncertainty, rather than dismissing it as having insufficient data.

The approach used to estimate geographic range size of species is also important when determining the extent to which a species range overlaps the protected area network. There is a similar trade-off when different types of data are used (Rondinini et al. 2006). For example, geographic ranges from occurrence data will have lower commission errors than geographic ranges estimated from distribution models. The consequence for the protected area analysis is that range models may predict areas to be present for a species when they are not present in an area, and this may lead to a false impression of protection for a species. On the other hand, occurrence data may under-represent populations across the range because survey effort was biased or inadequate. This could lead to inefficient allocation of protected areas as opportunities to protected sites can be missed and are assumed to absent for the target species. To mitigate this effect, the occurrence data were buffered to varying extents. This approach acknowledges the uncertainty of the occurrence location data and should reduce omission errors without incurring large costs in terms of commission errors.

A common goal in conservation planning is to expand protected area coverage to achieve a specific target of species representation or adequacy. In this study, a simple 'greedy' algorithm was developed and applied to the Aloe distributions. A potential limitation of this approach is that it may not find the optimal solution as a different sequence of site selection could achieve representation at a lower cost i.e. less area required for protection. A random element was added to the algorithm to provide alternative solutions, which contributed to a smaller area to reach the target of representing all species. A greedy algorithm has been shown to achieve solutions to the problem of site selection that are similar to optimal solutions derived by genetic algorithms (Moore et al. 2003; Joppa et al. 2013). Further work could focus on testing different algorithms and testing optimal solutions, but the simple greedy algorithm is adequate to highlight areas highly likely to be priorities for conservation. However, of greater urgency is to seek to obtain information on costs and other factors that could influence expansion of the protected area network in the Horn of Africa region as part of a systematic conservation planning approach.

Summary

Caveats to the various methods employed in the papers included in this thesis are documented in the papers themselves. However, some broader points can be made. Although occurrence data in the form of voucher specimens are often the best available data from which to determine geographic range for plants, they are biased due to collector patterns such as proximity to populated places or research centres and accessibility through transport routes (Stropp et al. 2016; Daru et al. 2018). Species distribution modelling, the process of combining occurrence data with environmental variables to predict suitable areas for a species, offers considerable promise, but is also subject to important pitfalls (Anderson 2012). Increasingly, distribution models are being applied specifically to Red Listing (Fivaz and Gonseth 2014; Syfert et al. 2014) and further testing should lead to clarity on how species distribution models can be applied to estimate geographic range metrics used in Red List assessment such as extent of occurrence (EOO) and area of occupancy (AOO).

The ongoing digitisation and mobilisation of museum and herbarium collections will increase the availability of relevant data for analysis, sometimes called Digitally Accessible Information (DAI) (Meyer et al. 2016) and will hopefully fill knowledge gaps. Furthermore, the growth of initiatives that support gathering of observation data (e.g. the citizen science project iNaturalist) will help to fill gaps in data collecting both spatially and temporally and this can support Red List assessment (Gardiner and Bachman 2016). Even the unstructured nature of DAI is becoming less problematic as new techniques are developed to determine population trends over time, potentially opening up non-geographic-based criteria such as Red List criterion A requiring data on population declines (Isaac et al. 2014).

iv) Original contribution to knowledge, relevance and impact

Plants play a vital role in supporting ecosystems, but their long-term persistence will depend on mitigating against the harmful effects of human-related threatening processes. The need to understand threat levels to plants is therefore of global importance, and this has been recognised in some of the major global conventions and frameworks that dominate international biodiversity conservation policy. However, plants are often absent from important analyses of biodiversity data, mainly as a result of plant knowledge gaps. An example published recently includes an analysis of biodiversity risk from cropland expansion and intensification, but only includes biodiversity data from birds, mammals, amphibians and reptiles (Kehoe et al. 2017). The papers included in this thesis respond in a very practical way to the challenges set by the major biodiversity and conservation targets, and close some of the plant data knowledge gaps (Figure 7), and it is also hoped that they will stimulate further scientific research on plants and will facilitate the inclusion of plants in global multi-taxon studies. In the following section the relevance and impacts of each paper are examined.

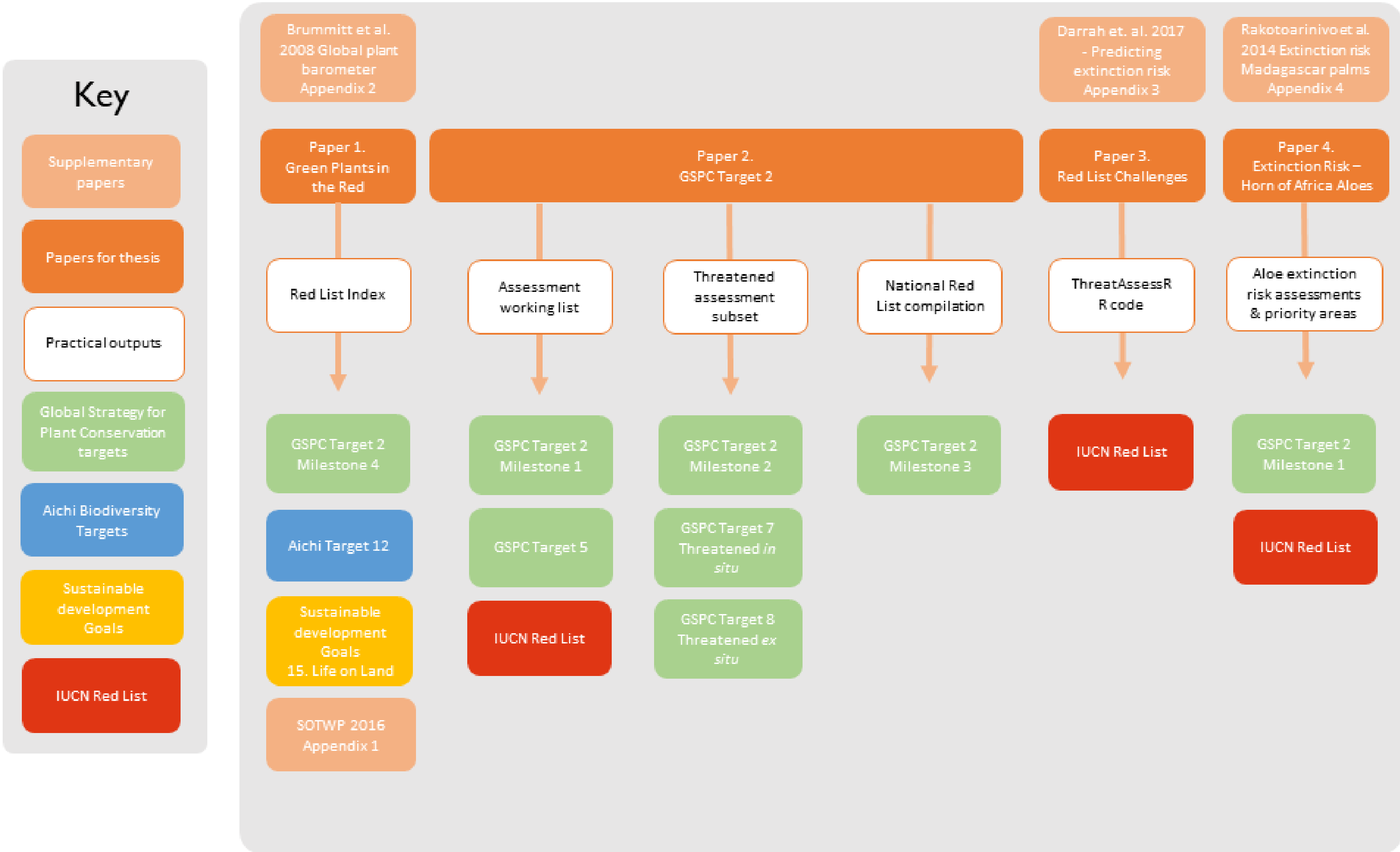


Figure 7.

How outputs from papers included in the thesis link to global policy conventions such as the Convention on Biological Diversity, the Sustainable Development Goals, the Global Strategy for Plant Conservation.

Paper 1 (Green Plants in the Red)

The foundation of this thesis is a considerable body of work including previous attempts to document levels of threat and extinction risk to plants globally as well as the hundreds of thousands of species assessments that have been completed by plant scientists. The Sampled Red List Index for Plants (SRLI) addressed a major gap in knowledge: the need for a quantitative estimate of extinction risk in plants. The Royal Botanic Gardens, Kew, was invited to contribute to the plant element of the SRLI project and I played a central role within this project as a species conservation assessment scientist. I co-ordinated teams of people to generate georeferenced digital specimen data and provided training on how to assess Red List status of plants, developing protocols including the 'desktop' approach. I reviewed most of the completed assessments and generated assessments for species in the Gnetales Gymnosperm group that are not covered by the Cycad or Conifer specialist groups. I jointly co-first authored the resulting paper **Paper 1 (Green Plants in the Red)** after more than 4,000 plant Red List assessments had been compiled. I contributed to the conception and design of the analysis, analysed data and contributed to the writing of the paper with the lead co-author. The project, on the whole, was only completed through the dedication of a large team of students, interns, volunteers and staff that all helped to build up a picture of plant extinction risk, as illustrated by the author list.

Our estimate of global extinction risk for plants was not the first, but the sample approach that we adopted provides a representative view that is built on a robust quantitative foundation of millions of specimen records and thousands of individual Red List assessments and so is a novel response to the question 'How threatened are plants?'. Furthermore, the resulting Red List Index value allowed plants to be compared for the first time with the other comprehensively Red Listed groups such as birds and mammals. We found that plants were experiencing the same level of threat as mammals. The development of the Index is also an important milestone as this is the baseline from which re-assessments can be made. Detecting genuine changes in Red List status across an entire group will show if threats are becoming more prevalent (Tittensor et al. 2014) or if conservation interventions are working (Hoffmann et al. 2010).

Impact: The output is the Red List Index (RLI) value or Sampled RLI and it is one of the most important global indicators for plant threat status. The RLI has been incorporated into the highest level biodiversity conventions and frameworks including the Aichi Biodiversity Targets (UNEP/CBD 2010a) and the Sustainable Development Goals (Brooks et al. 2015) as well as the GSPC – see Target 2, milestone 4 (UNEP/CBD 2010b) also see Figure 4. The Red List Index is one of the 'primary indicators' for Aichi Target 12: '*By 2020 the extinction of known threatened species* *has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained.*' and is the primary indicator for Sustainable Development Goal 15.5: '*Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.*' Although the GSPC does not set out which indicators should be used to report against the targets, milestone d: *An assessment of the threat status of a 'globally representative sample' of plant species based on a multi stakeholder effort by 2017.*' is very closely aligned with the Red List Index and the RLI can be used to report against it.

Results from this work were drawn on and presented in the 'Extinction risk' chapter of the first State of the World's Plants Report (Appendix 1). The report received substantial media attention with an equivalent advertising value (EAV) of £1,866,271, and the extinction risk headlines were reported more than any other topic (Kew press team, pers. comm). Furthermore it triggered a response in a high-impact journal from other plant extinction risk researchers that has started a stimulating conversation on the topic (Pimm and Raven 2017). To date, this paper has received 29 citations (Google Scholar) and has an Altmetric attention score of 98 (https://www.altmetric.com/details/4385912), which is reported to be the top 5% of all research outputs scored by Altmetric (Altmetric tracks the online activity surrounding articles and translates this into a score). This is likely due to the media attention generated from a big push from the Kew press team to highlight the paper's findings. A recent notification from the journal PLOS that published the article also notes that it is highly cited, being in the top 25% most cited PLOS ONE articles (Figure 8).

The SRLI is important for further scientific research in several ways. Firstly, it establishes a baseline extinction risk estimate for all plants and this can be used as a benchmark to compare plant taxa. For example in **Paper 4 (Extinction Risk – Horn of Africa Aloes)**, I note that 39% of the Aloes in the Horn of Africa are estimated to be threatened with extinction, which is much higher than the 21% global average derived from the SRLI for Plants. Secondly, the sample itself serves as an important dataset due to the fact that it is not biased and is therefore representative of plants. Gathering supplementary data on these plants such as traits, geographic distribution, in conjunction with the extinction risk data already established by SRLI, opens up the possibility of robust analyses of global plant patterns addressing questions such as: 'which traits are associated with higher levels of extinction risk?' and 'how are threatened plants distributed across gradients of climate and elevation?' It is hoped that the sample can be used for these kinds of analysis, and much more.

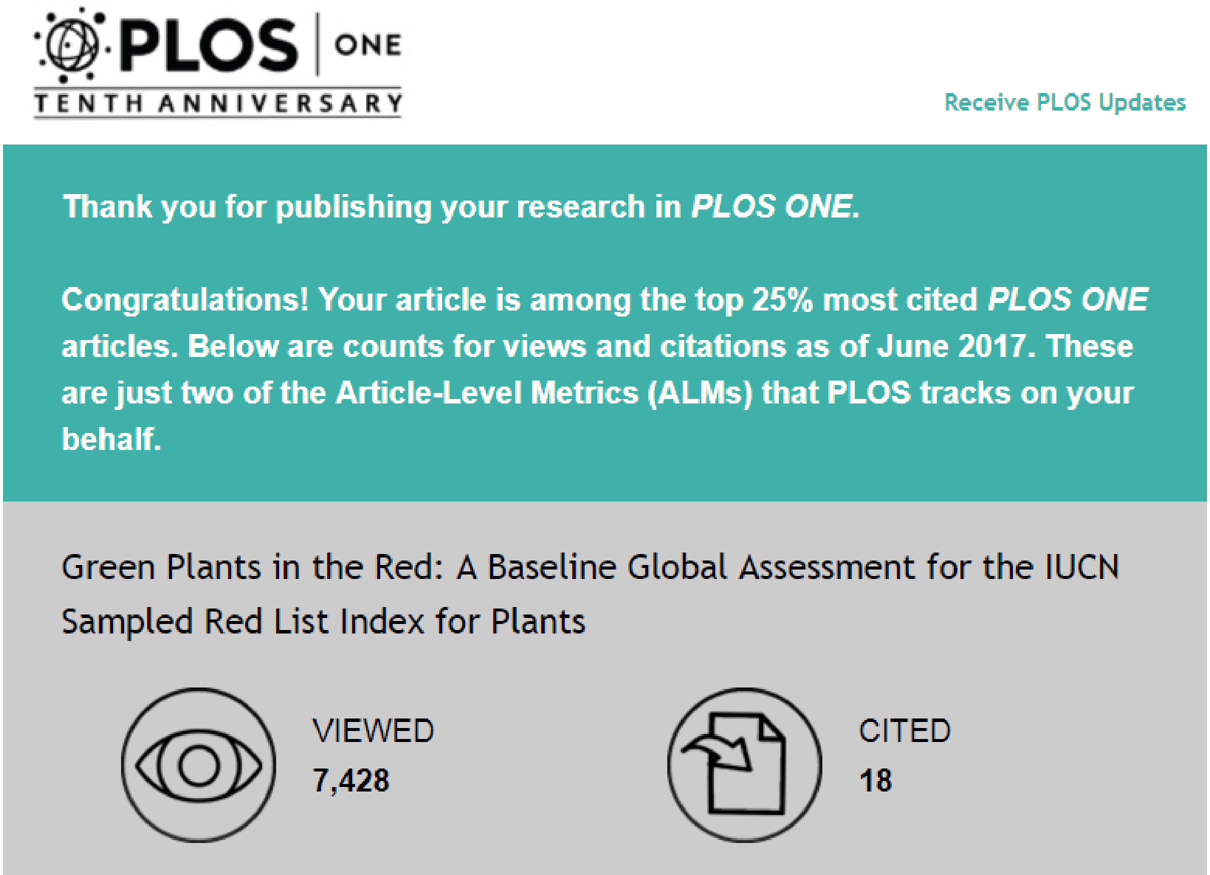


Figure 8.

Notification from PLOS journal regarding impact of Paper 1.

My role: The full authorship contribution is listed on the title page in Section B (page 61). In summary, my contribution included: conceiving and designing experiments, performing experiments, analysing data, contributing materials/analysis tools and writing the paper.

Paper 2 (GSPC Target 2)

The SRLI for plants serves its purpose of estimating overall global extinction risk in plants, but the SRLI sample is a necessarily small proportion of major plant clades, and therefore is less powerful for guiding conservation for the majority of the world's plants. The aim of **Paper 2 (GSPC Target 2)** is to respond directly to the challenge set out by Target 2 of the GSPC 'An assessment of the conservation status of all known plant species, as far as possible, to guide conservation action' (UNEP/CBD 2010b). For many years, since the first Red Data books were published, plant scientists have been assessing the status of plants using a variety of methods and systems, not just the IUCN Red List categories and criteria. Thousands of assessments have been published in a variety of formats e.g. accompanying floras and monographs, new species publications, National Red Lists and national reports to the CBD. Although there has been regular reporting on progress towards the GSPC targets (Secretariat of the CBD 2009; Sharrock et al. 2014) the reporting on Target 2 has so far focused on particular case studies such as countries that have recently produced a Red List or a project carrying out assessments of target groups such as crop wild relatives. I felt that there was a clear need to make a quantitative response to this target, firstly to acknowledge that progress had been made, but also to consolidate the data so that assessments, especially those of threatened species could be used to support conservation. I responded to the target by generating a preliminary list of conservation assessments from published sources (Figure 9) (Bachman 2014). The compilation included nearly 60,000 assessments, but a caveat with the approach is that the plant names were not matched to a taxonomic backbone meaning that assessments could have been linked to synonym or unresolved plant names and would give a misleading picture of progress and threat status for species. After a hiatus, a collaboration with Dr Malin Rivers, at Botanic Gardens Conservation International (BGCI), was developed with the aim of updating the preliminary list and to publish the results as well as the underlying assessment data so that it could be used to support conservation.

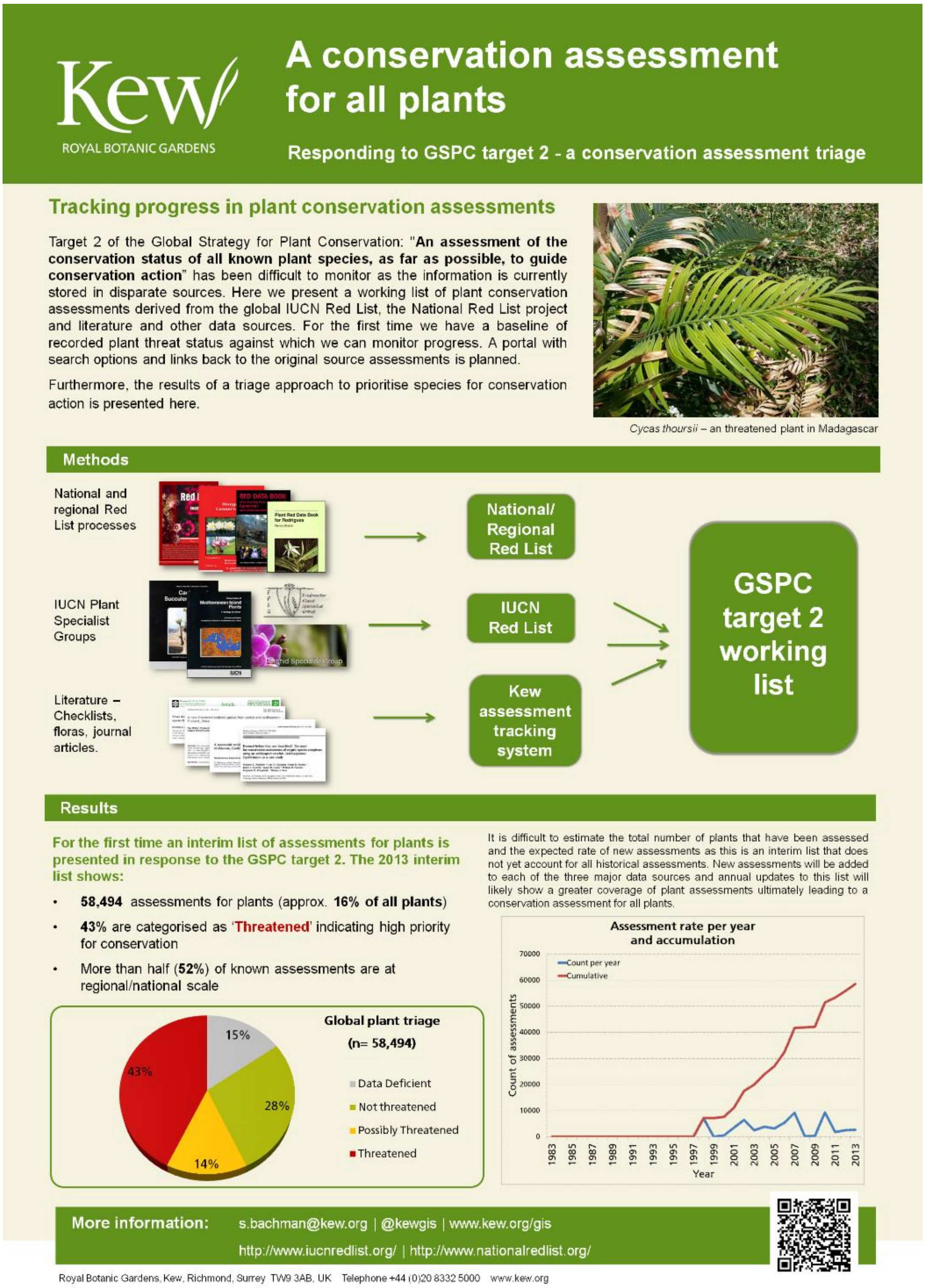


Figure 9

Poster presented at the 5th Global Botanic Gardens Conference in Dunedin, New Zealand. It outlines a proposed method for compiling existing conservation assessment data for plants in order to provide a baseline response to GSPC target 2 (Appendix 5).

Impact: This is the first time an attempt has been made to capture all digitally available plant conservation assessments and to reconcile them to a single taxonomic names backbone. The resulting output, which is now available online and hosted by Botanic Gardens Conservation International (BGCI) is called ThreatSearch [http://www.bgci.org/threat_search.php]. In this baseline response to Target 2 we note that 111,824 accepted species that have been assigned a conservation assessment and 27,148–32,542 species have been assessed at least once with a threatened category. In setting this baseline we also support other GSPC targets. For example, the subset of assessed species that were categorised as threatened species can support a response to GSPC targets 7 and 8. From this baseline, further assessments can be added and progress in achieving an assessment for all plants can be more accurately monitored. The availability of the assessments through a web resource also provides conservation practitioners with access to these data which could influence conservation decision making. A secondary output from **Paper 2 (GSPC Target 2)** is a review of the proportion of assessments that have been generated for each plant family. The intended consequence of this work is to highlight parts of the vascular plant phylogeny that have received less assessment attention than you would expect by chance alone. By highlighting those families that are under-assessed such as Asteraceae (Compositae), Orchidaceae and Rubiaceae, it is hoped that it will stimulate further assessment work.

My role: The full authorship contribution is listed on the title page in Section B (page 63). I contributed with Dr Rivers to a literature search to find digitally accessible plant conservation assessments in the literature that had been published since the preliminary list (Bachman 2014) was compiled, which led to a dataset of 241,919 unique assessments. Dr Rivers and I designed a plant names matching procedure using The Plant List (The Plant List 2013), which, after processing, revealed 111,824 accepted species had been assigned a conservation assessment. Dr Rivers carried out queries to determine the breakdown of species by threat status and scale, and I carried out analysis of assessment coverage by taxonomic families using a funnel plot. I led the writing of the subsequent manuscript and BGCI published the ThreatSearch dataset online.

Paper 3 (Red List Challenges)

The third paper in this thesis is a commentary on issues surrounding the Red List assessment of plants and is based on my experiences working in the field of plant conservation over the last 15 years. The inspiration for the paper initially came from a meeting of the IUCN Plant Conservation Sub-Committee in 2014 which I attended as a guest. Issues highlighted in **Paper 3 (Red List Challenges)** such as the use of different languages for documenting assessments and the change in documentation requirements to make it easier and faster to complete assessments, were already on the IUCN agenda and had been addressed to some extent. However, the meeting did not cover many additional issues and there was a clear need to share recent progress in plant Red Listing with a much wider audience of plant scientists and conservationists (i.e. those most likely to be affected by these developments) and also highlight where I felt there were ongoing challenges and opportunities.

I consulted with experts and colleagues that have close associations with the Red List to better understand what the major issues and ongoing challenges with Red List assessing and publication. I generated a dashboard using the plant data on the Red List to provide an easy to use interface to the plant data on the Red List (Figure 6). This also serves as a platform from which trends can be monitored and will help to track the impact of different decisions or developments that relate to Red Listing.

Impact: Paper 3 (Red List Challenges) provides a perspective on the present state of plants on the Red List and investigates reasons why there has been a lack of progress in developing the list. The ongoing challenges and opportunities for plant Red Listing are discussed. The paper outlines why it is important to aim for a complete Red List of all plants and offers some hope that this can be achieved by systematically addressing issues. It aims to stimulate more Red List activity and inform those that are interested in engaging with Red listing, but unfamiliar with the recent developments including rapid transfer of assessments and language support.

The opportunities highlighted in **Paper 3 (Red List Challenges)** to produce rapid assessments with minimal data and batch upload these to IUCN have inspired me already to investigate a programmatic solution. Using existing data resources like the Plants of the World Online portal (http://www.plantsoftheworldonline.org/) and the Global Biodiversity Information Facility (https://www.gbif.org/) I have developed scripts in R that can be used to predict if species are likely to be threatened or not and for those not threatened, to generate rapid assessments that fulfil the new requirements for Least Concern taxa. I hope to convert these scripts into a package or Shiny app and release more widely. The preliminary work is included in Appendix 6 and an ongoing development version is available on GitHub:
https://github.com/stevenpbachman/ThreatAssessR

Ultimately, the establishment of a more comprehensive Red List for plants does not only support conservation activities, it will also be a vitally important global plant dataset in its own right and will allow plants to be included within global biodiversity analyses. It is hoped that it will galvanise the plant science community and IUCN into working together towards a Red List for all plant species.

My role: The full authorship contribution is listed on the title page in Section B (page 64). In summary, I conceived the idea of the paper and led on the writing, providing the first draft. I then absorbed input from co-authors who helped to shape the manuscript. Although some ideas in the paper are not new, the compilation of issues and the development of the plant Red List dashboard are novel contributions to knowledge.

Paper 4 (Extinction Risk – Horn of Africa Aloes)

The final paper in this thesis is much more restricted in its taxonomic and geographic focus than the previous papers. It assesses the genus Aloe at a regional scale (the Horn of Africa), although Red List assessments were carried out using the global level criteria. The aim of the paper is to assess extinction risk and threats to Aloe in this region, to determine which species are at greatest risk and what are the important threatening processes. Extinction risk assessment revealed 39% of Aloe species were threatened, which is much higher than the global average as determined by the SRLI for Plants and other regional assessments, such as South Africa where 20% were assessed as threatened.

I performed a gap analysis to determine extent of conservation activities for Aloe in this region, both in terms of protected area coverage and ex situ representation. Recent growth in protected areas did not align well with Aloe distributions. Finally, a conservation prioritisation analysis was carried out to determine a minimum set of sites that would need to be protected in order to represent all Aloes. Countries like Somalia, with low levels of protected area coverage, represent opportunities for extending the PA network.

Although the techniques utilised in the study are not novel, they have never before been applied to the Aloes in the Horn of Africa region. The results therefore represent a contribution of knowledge for both the genus and the region. Further work is needed to look at the opportunities, costs and likelihood of success for extended protected areas. The baseline data on distribution, threats and extinction risk provided here can be incorporated into broader analyses, for example conservation planning with broader taxonomic coverage.

Impact: This paper provides much-needed new information on an area rich in plant diversity, but poor in available data. Establishing the extinction risk status for the genus Aloe in the Horn of Africa will hopefully kick-start conservation activity in this region and may help to support ongoing activities to restore and enhance the protected area network in countries like Somalia.

Baseline data such as distribution are also of importance for trying to answer questions on the origins of Aloes and to try and to explore patterns of endemism.

My role: The full authorship contribution is listed on the title page in Section B (page 65). The compilation of the Aloe dataset and assessment of extinction risk was led by Professor Sebsebe Demissew, Odile Weber and Dr Paul Wilkin. The threat data were generated through the Red List assessment process. I used these data to plot species distributions and compare them with the existing protected area network. I developed the greedy algorithm and undertook all analysis. All co-authors helped to conceive and design the experiments. I performed the experiments and analysed the data and led the writing of the paper.

v) Conclusion

Review of objectives

This thesis started with a simple question, 'how threatened are plants?', which was more fully defined as 'What is the contemporary level of threat to land plant species?'. This was subdivided into more specific questions: What proportion of plants are at risk of extinction, and how many species have been assessed? To respond to these questions, five objectives were developed:

1. Provide a quantitative baseline estimate for the percentage of plant species that are threatened with extinction
2. Establish a global indicator of plant extinction risk that can be used to report on global policy targets such as Aichi Biodiversity Target 12, GSPC Target 2 and Sustainable Development Goals Target 15
3. Establish a working list of plant threat assessments and a subset list of 'threatened' plants to inform GSPC Target 2 and to support other associated GSPC targets.
4. Using plants as a case study, review recent progress, ongoing challenges and opportunities for Red List assessment.
5. Assess extinction risk status and threats to *Aloe* occurring in the Horn of Africa, review conservation gaps for *Aloe* in this region and identify priorities for increased protection.

Paper 1 (Green Plants in the Red) responds directly to objectives 1 and 2 by estimating that 21% of plant species are threatened with extinction. Previous estimates ranged from 10 to 62% (RBG Kew 2016). Objective 2 is delivered because there is now a baseline assessment for the Sampled Red List Index for Plants that can be used to monitor progress against Aichi Biodiversity Target 12, GSPC Target 2 and the Sustainable Development Goal Target 15. We can now see how the level of threat to plants compares to other groups – as threatened as mammals, more threatened than birds, but not as threatened as amphibians. However, the baseline assessment presented here now needs to be followed up with a re-assessment of the sample in order to determine trend in threat status.

Paper 2 (GSPC Target 2) responds to objective 3 by providing the most comprehensive dataset of plant threat assessments to date. The results from this paper also answer the question: How many species have been assessed? We estimate between 73,000–90,000 species have been assessed at the global scale (21–26% of species). Classifying threat status of each species into consistent categories allowed quantification of the number of threatened species (27,000–35,000). As well as responding directly to GSPC Target 2, this baseline assessment can be used for future research such as analysis of other GPSC targets that require a list of 'threatened' species. Analysis of the taxonomic gaps in plant conservation assessments revealed families such as Asteraceae, Orchidaceae, and Rubiaceae that are assessed less than average when considering all families. However, there may also be patterns in the coverage of conservation assessments across regions. Further work should combine threat assessments with geographic distributions of plants to determine regions that are under-assessed and explore reasons for this.

Objective 4 is answered by **Paper 3 (Red List Challenges).** Reviewing patterns in the assessment of plants for the Red List reveals there has been slow progress in the addition of new species. In fact, the number of new assessments has, until recent years, not even matched the number of newly described plant species. Changes to the systems used to assess and document assessments as well as changes to rules and the relaxation of data requirements should all help to increase the rate of new assessments, but results suggest there has not yet been a step-change, such as a 10-fold increase in annual assessment output.

Aside from simply raising more funding to resource the production of assessments there are promising developments that should increase the rate of assessment productions. For example, extinction risk in plants can be predicted and automation can generate assessments – initially for non-threatened (Least Concern) species, but potentially also for threatened species. Training and development of the plant conservation network may also help, but further data is needed to test this.

Paper 4 (Extinction Risk – Horn of Africa Aloes) responds directly to objective 5. Threats to Aloe in the Horn of Africa and overall extinction risk are now better quantified. Expansion and intensification of crop farming and livestock farming as well as gathering of plants and unintentional effects of logging and wood harvesting are the major threats and 39% of species are threatened with extinction.

Aloe species, particularly threatened species, are not well represented in the protected area network, or within ex situ collections. Options to expand the protected area network could be achieved with limited additional protected area, but this needs to happen in countries like Somalia and South Sudan where protected area networks are currently poorly developed.

Future work

Two important milestones have been reached in this thesis: an estimate of overall extinction risk for plants and a working list of plant conservation assessments, both of which respond directly to global conservation targets. However, this static view of plant threat status needs to be followed with ongoing status assessments so that trends can be determined. The deadline for delivery of the Global Strategy for Plant Conservation (GSPC) and the Aichi 2020 targets is fast approaching and goals and targets are likely to be reviewed and reset (Mace et al. 2018). It is hoped that the results from this thesis can feed into this process by highlighting remaining gaps.

Thousands of plant conservation assessments have been generated, collated and analysed in the development of the four papers that make up this thesis. Some observations can be noted after working on these data, including the wide variety of standards used, and a large variation in the time taken to document an assessment, which in part is linked to the level of detail included in the assessment and the methods used to generate the assessment. Many assessment approaches are time consuming and rely on manual operations which restricts scalability, meaning the assessment of large groups cannot be achieved in a reasonable time-frame. Opportunities exist to utilise the growing amount of digitally accessible data (DAI) and apply modelling techniques to fast-track assessments. In **Paper 3 (Red List Challenges)** I highlight several ways in which a scientific approach has been used to support the generation of rapid and robust assessments, for example: using Earth Observation data on forest loss to infer population declines (Buchanan et al. 2008; Tracewski et al. 2016); applying statistical techniques to opportunistic occurrence data, such as the growing amount of DAI derived from citizen science initiatives (Isaac et al. 2014; Maes et al. 2015; Pocock et al. 2018) and using models to predict extinction to enable conservation triage (Darrah et al. 2017). Adopting these techniques could help to provide a more consistent approach to assessing species that is comparable and can also scale-up to allow assessment of diverse groups like plants, fungi and invertebrates. In addition, these approaches could be more efficient. An argument against the generation of assessments is their cost

(Bridgewater 2016), so reducing cost with efficiency gains means more resources for conservation on-the-ground.

A primary aim of this thesis has been to estimate the threat status of plants on a global scale and to respond to global conservation targets. However, conservation is not simply a cataloguing exercise and its success should be measured by the extent to which threats to species or rates of population decline are reduced. Identifying a species as threatened could raise the profile of that species, which in turn can leverage funding. Assessing a species as 'Critically Endangered' or 'Endangered' on the IUCN Red List confers that species some level of protection under the International Finance Corporation Critical Performance Standard 6 (IFC 2012), but to what extent has the threat status of a species been improved (i.e. reduced threat level), as a result of being assigned an assessment category? We know that conservation can work, and counter-factual arguments have been used to suggest that the conservation status of some species would have been much worse if conservation interventions had not been made (Hoffmann et al. 2010; Young et al. 2014), but would an un-assessed species have received conservation collaterally through for example habitat protection? To date there has been no synthesis of data on conservation success for plants by comparing species with or without assessments, or comparing impact of different types of assessment, and this is an opportunity for future work.

In summary, this thesis reveals that, on a global scale, plants are at a level of risk that is comparable to mammals, and that although considerable progress has been made in cataloguing threat status for plants, large gaps remain, with three quarters of plants yet to receive an assessment. Sub-global scale assessments have not been fully documented and may reveal greater coverage. The IUCN Red List of plants was examined to explore trends and responses to recent developments such as rule changes and technological improvements. There is limited evidence to suggest a change from the current trend in assessment output. However, further data are required to test the influence of factors such as the impact of training on the growth of assessor numbers and how this relates to the growth of assessments.

Although this thesis represents limited hypothesis-testing, it does demonstrate the ability to identify a problem, design a project, acquire and analyse data in a systematic and repeatable way and to generate new knowledge. The generation of knowledge, in this case, has a very practical outcome, which is to respond to global conservation targets. However, I hope to adopt a more hypothesis-driven approach for future work in response to the opportunities I have highlighted above.

vii) References

Akçakaya HR, Bennett EL, Brooks TM, et al (2018) Quantifying species recovery and conservation success to develop an IUCN Green List of Species. Conservation Biology 32:1128–1138. doi: 10.1111/cobi.13112

Anderson RP (2012) Harnessing the world's biodiversity data: promise and peril in ecological niche modeling of species distributions. Annals of the New York Academy of Sciences 1260:66–80. doi: 10.1111/j.1749-6632.2011.06440.x

Arponen A (2012) Prioritizing species for conservation planning. Biodiversity and Conservation 21:875–893. doi: 10.1007/s10531-012-0242-1

Bachman SP (2014) A conservation assessment for all plants. doi: 10.6084/M9.FIGSHARE.1045453

Bachman SP, Moat J, Hill A, et al (2011) Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. ZooKeys 150:117. doi: 10.3897/zookeys.150.2109

Baillie JEM, Collen B, Amin R, et al (2008) Toward monitoring global biodiversity. Conservation Letters 1:18–26. doi: 10.1111/j.1755-263X.2008.00009.x

Baker DJ, Garnett ST, O'Connor J, et al (2018) The conservation of abundance in nonthreatened species. Conservation Biology. doi: 10.1111/cobi.13197

Balmford A (2017) On positive shifting baselines and the importance of optimism. Oryx 51:191–192. doi: 10.1017/S0030605317000096

Balmford A, Bennun L, Ten Brink B, et al (2005) The convention on biological diversity's 2010 target. Science 307:212–213. doi: 10.1126/science.1106281

Balter M (2013) Archaeologists say the "Anthropocene" is here - But it began long ago. Science 340:261–262. doi: 10.1126/science.340.6130.261

Bar-On YM, Phillips R, Milo R (2018) The biomass distribution on Earth. Proceedings of the National Academy of Sciences of the United States of America 201711842. doi: 10.1073/pnas.1711842115

Barnosky AD, Hadly EA, Bascompte J, et al (2012) Approaching a state shift in Earth's biosphere. Nature 486:52–58. doi: 10.1038/nature11018

Barnosky AD, Lindsey EL, Villavicencio NA, et al (2016) Variable impact of late-Quaternary megafaunal extinction in causing ecological state shifts in North and South America. Proceedings of the National Academy of Sciences 113:856–861. doi: 10.1073/pnas.1505295112

Bennun L, Regan EC, Bird J, et al (2018) The Value of the IUCN Red List for Business Decision-Making. Conservation Letters 11:e12353. doi: 10.1111/conl.12353

Bland LM, Collen B, Orme CDL, Bielby J (2015) Predicting the conservation status of data-deficient species. Conservation Biology 29:250–259. doi: 10.1111/cobi.12372

Boakes EH, Rout TM, Collen B (2015) Inferring species extinction: the use of sighting records. Methods in Ecology and Evolution 6:678–687. doi: 10.1111/2041-210X.12365

Boyd C, Brooks TM, Butchart SHM, et al (2008) Spatial scale and the conservation of threatened species. Conservation Letters 1:37–43. doi: 10.1111/j.1755-263X.2008.00002.x

Brehm JM, Maxted N, Martins-Loução MA, Ford-Lloyd B V. (2010) New approaches for establishing conservation priorities for socio-economically important plant species. Biodiversity and Conservation 19:2715–2740. doi: 10.1007/s10531-010-9871-4

Breiner FT, Bergamini A (2018) Improving the estimation of area of occupancy for IUCN Red List assessments by using a circular buffer approach. Biodiversity and Conservation 27:2443–2448. doi: 10.1007/s10531-018-1555-5

Bridgewater P (2016) The Anthropocene biosphere: do threatened species, Red Lists, and protected areas have a future role in nature conservation? Biodiversity and Conservation 25:603–607. doi: 10.1007/s10531-016-1062-5

Brook BW, Ellis EC, Perring MP, et al (2013) Does the terrestrial biosphere have planetary tipping points? Trends in Ecology and Evolution 28:396–401. doi: 10.1016/j.tree.2013.01.016

Brooks TM, Butchart SHM, Cox NA, et al (2015) Harnessing biodiversity and conservation knowledge products to track the Aichi Targets and Sustainable Development Goals. Biodiversity 16:157–174. doi: 10.1080/14888386.2015.1075903

Brummitt N, Bachman S, Moat J (2008) Applications of the IUCN Red List: towards a global barometer for plant diversity. Endangered Species Research 6:127–135.

Buchanan GM, Butchart SHM, Dutson G, et al (2008) Using remote sensing to inform conservation status assessment: Estimates of recent deforestation rates on New Britain and the impacts upon endemic birds. Biological Conservation 141:56–66. doi: 10.1016/j.biocon.2007.08.023

Butchart SHM, Di Marco M, Watson JEM (2016) Formulating Smart Commitments on Biodiversity: Lessons from the Aichi Targets. Conservation Letters 9:457–468. doi: 10.1111/conl.12278

Butchart SHM, Lowe S, Martin RW, et al (2018) Which bird species have gone extinct? A novel quantitative classification approach. Biological Conservation 227:9–18. doi: 10.1016/j.biocon.2018.08.014

Butchart SHM, Resit Akçakaya H, Chanson J, et al (2007) Improvements to the Red List Index. PLoS ONE 2:8. doi: 10.1371/journal.pone.0000140

Butchart SHM, Stattersfield AJ, Baillie J, et al (2005) Using Red List Indices to measure progress towards the 2010 target and beyond. Philosophical transactions of the Royal Society of London Series B, Biological sciences 360:255–68. doi: 10.1098/rstb.2004.1583

Butchart SHM, Stattersfield AJ, Bennun L a, et al (2004) Measuring global trends in the status of biodiversity: red list indices for birds. PLoS biology 2:e383. doi: 10.1371/journal.pbio.0020383

Butchart SHM, Walpole M, Collen B, et al (2010) Global biodiversity: indicators of recent declines. Science (New York, NY) 328:1164–1168. doi: 10.1126/science.1187512

Cardillo M, Mace GM, Jones KE, et al (2005) Multiple Causes of High Extinction Risk in Large Mammal Species. Science 309:1239–1241. doi: 10.1126/science.1116030

Cardillo M, Meijaard E (2012) Are comparative studies of extinction risk useful for conservation? Trends in Ecology and Evolution 27:167–171. doi: 10.1016/j.tree.2011.09.013

Cardinale BJ, Duffy JE, Gonzalez A, et al (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67. doi: 10.1038/nature11148

Cardoso P, Erwin TL, Borges PAV, New TR (2011) The seven impediments in invertebrate conservation and how to overcome them. Biological Conservation 144:2647–2655. doi:

10.1016/j.biocon.2011.07.024

CBD (2010) X/17. Consolidated update of the Global Strategy for Plant Conservation 2011 - 2020.

Ceballos G, Ehrlich PR, Barnosky AD, et al (2015) Accelerated modern human – induced species losses: entering the sixth mass extinction. Sciences Advances 1:1–5. doi: 10.1126/sciadv.1400253

Clausnitzer V, Kalkman VJ, Ram M, et al (2009) Odonata enter the biodiversity crisis debate: The first global assessment of an insect group. Biological Conservation 142:1864–1869. doi: 10.1016/j.biocon.2009.03.028

Collen B, Baillie JEM (2010) Barometer of life: sampling. Science (New York, NY) 329:140; author reply 141-2. doi: 10.1126/science.329.5988.140-a

Collen B, Dulvy NK, Gaston KJ, et al (2016) Clarifying misconceptions of extinction risk assessment with the IUCN Red List. Biology Letters. doi: doi:10.1098/rsbl.2015.0843

Colloff MJ, Lavorel S, van Kerkhoff LE, et al (2017) Transforming conservation science and practice for a postnormal world. Conservation Biology 31:1008–1017. doi: 10.1111/cobi.12912

Costanza R, de Groot R, Sutton P, et al (2014) Changes in the global value of ecosystem services. Global Environmental Change 26:152–158. doi: 10.1016/j.gloenvcha.2014.04.002

Council of European Communities (1992) Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Council of the European Communities (CEC).

Courchamp F, Clutton-Brock T, Grenfell B (1999) Inverse density dependence and the Allee effect. Trends in Ecology & Evolution 14:405–410. doi: 10.1016/S0169-5347(99)01683-3

Cronk Q (2016) Plant extinctions take time. Science 353:446–447. doi: 10.1126/science.aag1794

Crutzen PJ (2002) Geology of mankind. Nature 415:23. doi: 10.1038/415023a

Dahlberg A, Mueller GM (2011) Applying IUCN red-listing criteria for assessing and reporting on the conservation status of fungal species. Fungal Ecology 4:147–162. doi: 10.1016/j.funeco.2010.11.001

Darrah SE, Bland LM, Bachman SP, et al (2017) Using coarse-scale species distribution data to predict extinction risk in plants. Diversity and Distributions 23:435–447. doi: 10.1111/ddi.12532

Daru BH, Park DS, Primack RB, et al (2018) Widespread sampling biases in herbaria revealed from large-scale digitization. New Phytologist 217:939–955. doi: 10.1111/nph.14855

Davies RG, Orme CDL, Olson V, et al (2006) Human impacts and the global distribution of extinction risk. Proceedings Biological sciences / The Royal Society 273:2127–2133. doi: 10.1098/rspb.2006.3551

Di Marco M, Chapman S, Althor G, et al (2017) Changing trends and persisting biases in three decades of conservation science. Global Ecology and Conservation 10:32–42. doi: 10.1016/j.gecco.2017.01.008

Dirzo R, Young HS, Galetti M, et al (2014) Defaunation in the Anthropocene. Science 345:401–406. doi: 10.1126/science.1251817

Doherty TS, Bland LM, Bryan BA, et al (2018) Expanding the Role of Targets in Conservation Policy. Trends in Ecology and Evolution 33:809–812. doi: 10.1016/j.tree.2018.08.014

Duffy JE, Godwin CM, Cardinale BJ (2017) Biodiversity effects in the wild are common and as strong as key drivers of productivity. Nature 549:261–264. doi: 10.1038/nature23886

Ellis EC (2011) Anthropogenic transformation of the terrestrial biosphere. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 369:1010–1035. doi: 10.1098/rsta.2010.0331

Ellis EC, Antill EC, Kreft H (2012) All Is Not Loss: Plant Biodiversity in the Anthropocene. PLoS ONE 7:e30535. doi: 10.1371/journal.pone.0030535

Ellis EC, Ramankutty N (2008) Putting people in the map: Anthropogenic biomes of the world. Frontiers in Ecology and the Environment 6:439–447.

Fisher DO, Owens IPF (2004) The comparative method in conservation biology. Trends in Ecology & Evolution 19:391–398. doi: 10.1016/J.TREE.2004.05.004

Fivaz FP, Gonseth Y (2014) Using species distribution models for IUCN Red Lists of threatened species. Journal of Insect Conservation 18:427–436. doi: 10.1007/s10841-014-9652-6

Flather CH, Hayward GD, Beissinger SR, Stephens PA (2011) Minimum viable populations: is there a 'magic number' for conservation practitioners? Trends in Ecology & Evolution 26:307–316. doi: 10.1016/J.TREE.2011.03.001

Gardiner LM, Bachman SP (2016) The role of citizen science in a global assessment of extinction risk in palms (Arecaceae). Botanical Journal of the Linnean Society 182:543–550. doi: 10.1111/boj.12402

Gascon C, Brooks TM, Contreras-MacBeath T, et al (2015) The Importance and Benefits of Species. Current Biology 25:R431–R438. doi: 10.1016/J.CUB.2015.03.041

Gaston KJ (1994) Measuring geographic range sizes. Ecography 17:198–205. doi: 10.1111/j.1600-0587.1994.tb00094.x

Gaston KJ (2003) The Structure And Dynamics Of Geographic Ranges. Oxford University Press

Gaston KJ, Fuller RA (2009) The sizes of species' geographic ranges. Journal of Applied Ecology 46:1–9. doi: 10.1111/j.1365-2664.2008.01596.x

Gaston KJ, Fuller RA (2008) Commonness, population depletion and conservation biology. Trends in Ecology & Evolution 23:14–19. doi: 10.1016/J.TREE.2007.11.001

Grantham HS, Pressey RL, Wells JA, Beattie AJ (2010) Effectiveness of Biodiversity Surrogates for Conservation Planning: Different Measures of Effectiveness Generate a Kaleidoscope of Variation. PLoS ONE 5:11430. doi: 10.1371/journal.pone.0011430

Grenyer R, Orme CDL, Jackson SF, et al (2006) Global distribution and conservation of rare and threatened vertebrates. Nature 444:93–96.

Hayward MW, Child MF, Kerley GIH, et al (2015) Ambiguity in guideline definitions introduces assessor bias and influences consistency in IUCN Red List status assessments. Frontiers in Ecology and Evolution 3:87. doi: 10.3389/fevo.2015.00087

Heywood VH (2017) Plant conservation in the Anthropocene – Challenges and future prospects. Plant Diversity 39:314–330. doi: 10.1016/j.pld.2017.10.004

Hoffmann M, Hilton-Taylor C, Angulo A, et al (2010) The impact of conservation on the status of the world's vertebrates. Science (New York, NY) 330:1503–9. doi: 10.1126/science.1194442

Hooper DU, Adair EC, Cardinale BJ, et al (2012) A global synthesis reveals biodiversity loss as a major driver of ecosystem change. Nature 486:105–108. doi: 10.1038/nature11118

Huang Y, Chen Y, Castro-Izaguirre N, et al (2018) Impacts of species richness on productivity in a large-scale subtropical forest experiment. Science (New York, NY) 362:80–83. doi: 10.1126/science.aat6405

Hulme PE, Bernard-Verdier M, Bufford JL, Godsoe W (2015) Rapid Anthropocene Speciation Reveals Pull of the Recent: A Response to Thomas. Trends in Ecology and Evolution 30:635–636.

Humphries CJ, Williams PH, Vane-Wright RI (1995) Measuring Biodiversity Value for Conservation. Annual Review of Ecology and Systematics 26:93–111.

IFC (2012) Performance Standard 6 Biodiversity Conservation and Sustainable Management of Living Natural Resources. http://www.ifc.org/wps/wcm/connect/bff0a28049a790d6b835faa8c6a8312a/PS6_English_2012.pdf?MOD=AJPERES.

IPBES (2018) Intergovernmental Platform on Biodiversity and Ecosystem Services. https://www.ipbes.net/. Accessed 22 Nov 2018

Isaac NJB, van Strien AJ, August TA, et al (2014) Statistics for citizen science: extracting signals of change from noisy ecological data. Methods in Ecology and Evolution 5:1052–1060. doi: 10.1111/2041-210X.12254

Isbell F, Gonzalez A, Loreau M, et al (2017) Linking the influence and dependence of people on biodiversity across scales. Nature 546:65–72.

IUCN (2001) IUCN Red List Categories and Criteria: version 3.1. Prepared by the IUCN Species Survival Commission

IUCN (2012) IUCN Red List Categories and Criteria: Version 3.1. Second edition. IUCN, Gland, Switzerland and Cambridge, UK

IUCN (2017) Table 1: Numbers of threatened species by major groups of organisms (1996–2017). http://cmsdocs.s3.amazonaws.com/summarystats/2017-3_Summary_Stats_Page_Documents/2017_3_RL_Stats_Table_1.pdf.

IUCN Red List (2012) IUCN Red List of Threatened Species. Version 2012-1.

IUCN Standards And Petitions Subcommittee (2014) Guidelines for using the IUCN Red List Categories and Criteria. Version 11 (February 2014). Prepared by the Standards and Petitions Working Group of the IUCN SSC Biodiversity Assessments SubCommittee in August 2008 1:86.

Jepson P (2018) Recoverable Earth: a twenty-first century environmental narrative. Ambio 1–8. doi: 10.1007/s13280-018-1065-4

Johnson CN (2009) Ecological consequences of Late Quaternary extinctions of megafauna. Proceedings Biological sciences 276:2509–19. doi: 10.1098/rspb.2008.1921

Joppa LN, Butchart SHM, Hoffmann M, et al (2016) Impact of alternative metrics on estimates of extent of occurrence for extinction risk assessment. Conservation Biology 30:362–370. doi: 10.1111/cobi.12591

Joppa LN, Visconti P, Jenkins CN, Pimm SL (2013) Achieving the convention on biological diversity's goals for plant conservation. Science (New York, NY) 341:1100–3. doi: 10.1126/science.1241706

Kehoe L, Romero-Muñoz A, Polaina E, et al (2017) Biodiversity at risk under future cropland expansion and intensification. Nature Ecology & Evolution 1:1129–1135. doi: 10.1038/s41559-017-0234-3

Keith DA, Butchart SHM, Regan HM, et al (2017) Inferring extinctions I: A structured method using information on threats. Biological Conservation 214:320–327. doi: 10.1016/j.biocon.2017.07.026

Keith DA, Rodríguez JP, Rodríguez-Clark KM, et al (2013) Scientific foundations for an IUCN Red List of ecosystems. PloS one 8:e62111. doi: 10.1371/journal.pone.0062111

Koch PL, Barnosky AD (2006) Late Quaternary Extinctions: State of the Debate. Annual Review of Ecology, Evolution, and Systematics 37:215–250. doi: 10.1146/annurev.ecolsys.34.011802.132415

Kukkala AS, Moilanen A (2013) Core concepts of spatial prioritisation in systematic conservation planning. Biological Reviews 88:443–464. doi: 10.1111/brv.12008

Lamoreux J, Akcakaya HR, Bennun L, et al (2003) Value of the IUCN Red List. Trends in Ecology & Evolution 18:214–215. doi: 10.1016/S0169-5347(03)00090-9

Larsen FW, Bladt J, Balmford A, Rahbek C (2012) Birds as biodiversity surrogates: will supplementing birds with other taxa improve effectiveness? Journal of Applied Ecology 49:349–356. doi: 10.1111/j.1365-2664.2011.02094.x

Leopold A (1949) A Sand County Almanac and sketches here and there. Oxford University Press, New York

Lindenmayer DB, Wood JT, McBurney L, et al (2011) How to make a common species rare: A case against conservation complacency. Biological Conservation 144:1663–1672. doi: 10.1016/J.BIOCON.2011.02.022

Mace G, Collar NJ, Gaston KJ, et al (2008) Quantification of extinction risk: IUCN's system for classifying threatened species. Conservation Biology 22:1424–1442. doi: 10.1111/j.1523-1739.2008.01044.x.

Mace GM (2014) Whose conservation? Science 345:1558–1560. doi: 10.1126/science.1254704

Mace GM, Barrett M, Burgess ND, et al (2018) Aiming higher - bending the curve of biodiversity loss. Nature Sustainability 1:448–451. doi: 10.1038/s41893-018-0130-0

Mace GM, Lande R (1991) Assessing Extinction rates: Toward a Reevaluation of IUCN Treatened Species Categories. Conservation Biology 5:148–157.

Mace GM, Reyers B, Alkemade R, et al (2014) Approaches to defining a planetary boundary for biodiversity. Global Environmental Change 28:289–297. doi: 10.1016/J.GLOENVCHA.2014.07.009

Maes D, Isaac NJB, Harrower CA, et al (2015) The use of opportunistic data for IUCN Red List assessments. Biological Journal of the Linnean Society n/a-n/a. doi: 10.1111/bij.12530

Mancina C, Echenique-Diaz L, Tejedor A, et al (2007) Endemics under threat: an assessment of the conservation status of Cuban bats. Hystrix, the Italian Journal of Mammalogy. doi: 10.4404/hystrix-18.1-4388

Marco M Di, Buchanan GM, Szantoi Z, et al (2014) Drivers of extinction risk in African mammals: the interplay of distribution state, human pressure, conservation response and species biology. Phil Trans R Soc. doi: https://doi.org/10.1098/rstb.2013.0198

Marsh C, Barwell LJ, Gavish Y, Kunin WE (2018) Downscale: An R Package for Downscaling Species Occupancy from Coarse-Grain Data to Predict Occupancy at Fine-Grain Sizes.

Journal of Statistical Software. doi: doi: 10.18637/jss.v086.c03

Marsh H, Dennis A, Hines H, et al (2007) Optimizing allocation of management resources for wildlife. Conservation Biology 21:387–399. doi: 10.1111/j.1523-1739.2006.00589.x

Martin TG, Nally S, Burbidge AA, et al (2012) Acting fast helps avoid extinction. Conservation Letters 5:274–280. doi: 10.1111/j.1755-263X.2012.00239.x

Maycock CR, Kettle CJ, Khoo E, et al (2012) A Revised Conservation Assessment of Dipterocarps in Sabah. Biotropica 44:649–657. doi: 10.1111/j.1744-7429.2011.00852.x

McCarthy MA, Thompson CJ, Garnett ST (2008) Optimal investment in conservation of species. Journal of Applied Ecology 45:1428–1435. doi: 10.1111/j.1365-2664.2008.01521.x

Meyer C, Weigelt P, Kreft H (2016) Multidimensional biases, gaps and uncertainties in global plant occurrence information. Ecology letters. doi: 10.1111/ele.12624

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, Washington DC.

Moat J, Bachman SP, Field R, Boyd DS (2018) Refining area of occupancy to address the modifiable areal unit problem in ecology and conservation. Conservation Biology 32:1278–1289. doi: 10.1111/cobi.13139

Moore JL, Folkmann M, Balmford A, et al (2003) Heuristic and optimal solutions for set-covering problems in conservation biology. Ecography 26:595–601. doi: 10.1034/j.1600-0587.2003.03467.x

Muir J (1890) The Treasures of the Yosemite. The Century Magazine

Nelson GC (2011) Untangling the Environmentalist's Paradox: Better Data, Better Accounting, and Better Technology Will Help. BioScience 61:9–10. doi: 10.1525/bio.2011.61.1.3

Newbold T, Hudson LN, Arnell AP, et al (2016) Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353:291–288. doi: 10.1126/science.aaf2201

Newbold T, Tittensor DP, Harfoot MBJ, et al (2018) Non-linear changes in modelled terrestrial ecosystems subjected to perturbations. bioRxiv. doi: 10.1101/439059

Nic Lughadha E, Baillie J, Barthlott W, et al (2005) Measuring the fate of plant diversity: towards a foundation for future monitoring and opportunities for urgent action. Philosophical Transactions of the Royal Society B: Biological Sciences 360:359–372. doi: 10.1098/rstb.2004.1596

O'Donnell K, Sharrock S (2017) The contribution of botanic gardens to ex situ conservation through seed banking. Plant Diversity 39:373–378. doi: 10.1016/J.PLD.2017.11.005

Oliver TH, Heard MS, Isaac NJB, et al (2015) Biodiversity and Resilience of Ecosystem Functions. Trends in Ecology and Evolution 30:673–684. doi: 10.1016/j.tree.2015.08.009

Paton A, Lughadha EN (2011) The irresistible target meets the unachievable objective: what have 8 years of GSPC implementation taught us about target setting and achievable objectives? Botanical Journal of the Linnean Society 166:250–260. doi: doi:10.1111/j.1095-8339.2011.01155.x

Pearson RG (2016) Reasons to Conserve Nature. Trends in Ecology and Evolution 31:366–371. doi: 10.1016/j.tree.2016.02.005

Peters H, O'Leary BC, Hawkins JP, Roberts CM (2015) Identifying species at extinction risk using global models of anthropogenic impact. Global Change Biology 21:618–628. doi: 10.1111/gcb.12749

Piccolo JJ, Washington H, Kopnina H, Taylor B (2018) Why conservation scientists should re-embrace their ecocentric roots. Conservation Biology 32:959–961. doi: 10.1111/cobi.13067

Pimm SL, Jenkins CN, Abell R, et al (2014) The biodiversity of species and their rates of extinction, distribution, and protection. Science (New York, NY) 344:1246752. doi: 10.1126/science.1246752

Pimm SL, Raven PH (2017) The Fate of the World's Plants. Trends in Ecology & Evolution 32:317–320. doi: 10.1016/j.tree.2017.02.014

Pocock MJO, Chandler M, Bonney R, et al (2018) A Vision for Global Biodiversity Monitoring With Citizen Science. Advances in Ecological Research 59:169–223. doi: 10.1016/BS.AECR.2018.06.003

Possingham HP, Andelman SJ, Burgman MA, et al (2002) Limits to the use of threatened species lists. Trends in Ecology & Evolution 17:503–507. doi: 10.1016/S0169-5347(02)02614-9

R Core Team (2016) R: A language and environment for statistical computing.

Raudsepp-Hearne C, Peterson GD, Tengö M, et al (2010) Untangling the Environmentalist's Paradox: Why Is Human Well-being Increasing as Ecosystem Services Degrade? BioScience 60:576–589. doi: 10.1525/bio.2010.60.8.4

Raup DM (1994) The role of extinction in evolution. Proceedings of the National Academy of Sciences 91:6758–6763. doi: 10.1073/pnas.91.15.6758

RBG Kew (2016) The State of the World's Plants Report – 2016.

Ricketts TH, Dinerstein E, Boucher T, et al (2005) Pinpointing and preventing imminent extinctions. PNAS 102:18497–18501. doi: www.pnas.org_cgi_doi_10.1073_pnas.0509060102

Rockström J, Steffen W, Noone K, et al (2009) A safe operating space for humanity. Nature 461:472–475. doi: 10.1038/461472a

Rodrigues ASL, Brooks TM (2007) Shortcuts for Biodiversity Conservation Planning: The Effectiveness of Surrogates. Annual Review of Ecology, Evolution, and Systematics 38:713–737. doi: 10.1146/annurev.ecolsys.38.091206.095737

Rodrigues ASL, Pilgrim JD, Lamoreux JF, et al (2006) The value of the IUCN Red List for conservation. Trends in ecology evolution 21:71–6. doi: 10.1016/j.tree.2005.10.010

Rondinini C, Di Marco M, Visconti P, et al (2013) Update or outdate: long-term viability of the IUCN Red List. Conservation Letters 7:126–130. doi: 10.1111/conl.12040

Rondinini C, Wilson KA, Boitani L, et al (2006) Tradeoffs of different types of species occurrence data for use in systematic conservation planning. Ecology Letters 9:1136–1145. doi: 10.1111/j.1461-0248.2006.00970.x

Rule S, Brook BW, Haberle SG, et al (2012) The aftermath of megafaunal extinction: Ecosystem transformation in Pleistocene Australia. Science 335:1483–1486. doi: 10.1126/science.1214261

Scholes RJ, Biggs R (2005) A biodiversity intactness index. Nature 434:45–49. doi: 10.1038/nature03289

Secretariat of the CBD (1973) Convention on International Trade in Endangered Species of Wild Fauna and Flora.

Secretariat of the CBD (2009) The Convention on Biological Diversity Plant Conservation Report: A Review of Progress in Implementing the Global Strategy of Plant Conservation (GSPC). Montreal

Secretariat of the Convention on Biological Diversity (2014) Global Biodiversity Outlook 4. Montreal, Quebec

Shaffer ML (1981) Minimum Population Sizes for Species Conservation. BioScience 31:131–134. doi: 10.2307/1308256

Shapiro B (2017) Pathways to de-extinction: how close can we get to resurrection of an extinct species? Functional Ecology 31:996–1002. doi: 10.1111/1365-2435.12705

Sharrock S, Oldfield S, Wilson O (2014) Plant conservation report 2014: A review of progress in implementation of the Global Strategy for Plant Conservation 2011-2020.

Silvertown J (2015) Have Ecosystem Services Been Oversold? Trends in Ecology & Evolution 30:641–648. doi: 10.1016/j.tree.2015.08.007

Soulé ME (1985) What Is Conservation Biology? BioScience 35:727–734. doi: 10.2307/1310054

Steffen W, Broadgate W, Deutsch L, et al (2015a) The trajectory of the Anthropocene: The Great Acceleration. The Anthropocene Review 2:81–98. doi: 10.1177/2053019614564785

Steffen W, Crutzen PJ, McNeill JR (2007) The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature. AMBIO: A Journal of the Human Environment 36:614–621.

Steffen W, Richardson K, Rockström J, et al (2015b) Sustainability. Planetary boundaries: guiding human development on a changing planet. Science (New York, NY) 347:1259855. doi: 10.1126/science.1259855

Steffen W, Sanderson RA, Tyson PD, et al (2004) Global Change and the Earth System, 1st edn. Springer-Verlag Berlin Heidelberg

Stropp J, Ladle RJ, M. Malhado AC, et al (2016) Mapping ignorance: 300 years of collecting flowering plants in Africa. Global Ecology and Biogeography 25:1085–1096. doi: 10.1111/geb.12468

Stuart SN, Collen B (2013) Conserving Biodiversity in a Target-Driven World. In: Biodiversity Monitoring and Conservation. Wiley-Blackwell, Oxford, UK, pp 421–438

Stuart SN, Wilson EO, McNeely JA, et al (2010) Ecology. The barometer of life. Science (New York, NY) 328:177.

Syfert MM, Joppa L, Smith MJ, et al (2014) Using species distribution models to inform IUCN Red List assessments. Biological Conservation 177:174–184. doi: 10.1016/j.biocon.2014.06.012

Tallavaara M, Eronen JT, Luoto M (2018) Productivity, biodiversity, and pathogens influence the global hunter-gatherer population density. Proceedings of the National Academy of Sciences of the United States of America 115:1232–1237. doi: 10.1073/pnas.1715638115

Tear TH, Kareiva P, Angermeier PL, et al (2005) How Much Is Enough? The Recurrent Problem of Setting Measurable Objectives in Conservation. BioScience 55:835–849.

The Plant List (2013) The Plant List Version 1.1. http://www.theplantlist.org. Accessed 12 Nov 2015

Thomas CD (2015) Rapid acceleration of plant speciation during the Anthropocene. Trends in Ecology and Evolution 30:448–455. doi: 10.1016/j.tree.2015.05.009

Thompson CJ, Koshkina V, Burgman MA, et al (2017) Inferring extinctions II: A practical, iterative model based on records and surveys. Biological Conservation 214:328–335. doi: 10.1016/j.biocon.2017.07.029

Tittensor DP, Walpole M, Hill SLL, et al (2014) A mid-term analysis of progress toward international biodiversity targets. Science 346:241–244. doi: 10.1126/science.1257484

Tracewski Ł, Butchart SHM, Marco M Di, et al (2016) Toward quantification of the impact of 21st-century deforestation on the extinction risk of terrestrial vertebrates. Conservation Biology 30:1070–1079. doi: 10.1111/cobi.12715

Traill LW, Bradshaw CJA, Brook BW (2007) Minimum viable population size: A meta-analysis of 30 years of published estimates. Biological Conservation 139:159–166. doi: 10.1016/J.BIOCON.2007.06.011

Traill LW, Brook BW, Frankham RR, Bradshaw CJA (2010) Pragmatic population viability targets in a rapidly changing world. Biological Conservation 143:28–34. doi: 10.1016/J.BIOCON.2009.09.001

Troudet J, Grandcolas P, Blin A, et al (2017) Taxonomic bias in biodiversity data and societal preferences. Scientific Reports 7:9132. doi: 10.1038/s41598-017-09084-6

UK National Ecosystem Assessment (2011) The UK National Ecosystem Assessment Technical Report. UNEP-WCMC, Cambridge

UNEP/CBD (2002) VI/9. UNEP/CBD/COP/6/20.

UNEP/CBD (2010a) The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. In: UNEP/CBD/COP/DEC/X/2. https://www.cbd.int/decision/cop/?id=12268.

UNEP/CBD (2010b) Global Strategy for Plant Conservation: Technical rationale, justification for updating and suggested milestones andindicators.

United Nations (1992) Convention on Biological Diversity.

United Nations Department of Economic and Social Affairs (UN DESA) (2018) Sustainable Development Goals Report 2018.

Vellend M, Baeten L, Becker-Scarpitta A, et al (2017) Plant Biodiversity Change Across Scales During the Anthropocene. Annual Review of Plant Biology 68:563–586. doi: 10.1146/annurev-arplant-042916-040949

Vié J-C, Hilton-Taylor C, Pollock C, et al (2009) The IUCN Red List: a key conservation tool. In: Wildlife in a changing world - an analysis of the IUCN Red List of Threatened Species. pp 1–14

Vitousek PM, D'Antonio CM, Loope LL, et al (1997) Introduced species: A significant component of human-caused global change. New Zealand Journal of Ecology 21:1–16.

Walker M, Johnsen S, Rasmussen SO, et al (2009) Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. Journal of Quaternary Science 24:3–17. doi: 10.1002/jqs.1227

Waters CN, Zalasiewicz J, Summerhayes C, et al (2016) The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science (New York, NY) 351:aad2622. doi: 10.1126/science.aad2622

Watson JE, Shanahan DF, Di Marco M, et al (2016) Catastrophic Declines in Wilderness Areas

Undermine Global Environment Targets. doi: 10.1016/j.cub.2016.08.049

Watson JEM, Dudley N, Segan DB, Hockings M (2014) The performance and potential of protected areas. Nature 515:67–73. doi: 10.1038/nature13947

Williams M, Zalasiewicz J, Haff PK, et al (2015) The Anthropocene biosphere. The Anthropocene Review 2:196–219. doi: 10.1177/2053019615591020

Williams SJ, Jones JPG, Clubbe C, et al (2012) Why are some biodiversity policies implemented and others ignored? Lessons from the uptake of the Global Strategy for Plant Conservation by botanic gardens. Biodiversity and Conservation 21:175–187. doi: 10.1007/s10531-011-0174-1

Willis F, Moat J, Paton A (2003) Defining a role for herbarium data in Red List assessments: a case study of Plectranthus from eastern and southern tropical Africa. Biodiversity and Conservation 12:1537–1552. doi: 10.1023/a:1023679329093

Woodcock P, Hayward MW (2016) Moving the Goalposts: Possible Effects of Changes in Opportunity Costs on Conservation Triage. Frontiers in Ecology and Evolution 4:113. doi: 10.3389/fevo.2016.00113

Wyse Jackson P, Kennedy K (2009) The Global Strategy for Plant Conservation: a challenge and opportunity for the international community. Trends in plant science 14:578–80. doi: 10.1016/j.tplants.2009.08.011

Young RP, Hudson MA, Terry AMR, et al (2014) Accounting for conservation: Using the IUCN Red List Index to evaluate the impact of a conservation organization. Biological Conservation 180:84–96. doi: 10.1016/j.biocon.2014.09.039

B. Results – Published and un-published papers

Paper 1. Green Plants in the Red

Green Plants in the Red: a baseline global assessment for the IUCN Sampled Red List Index for Plants

Status:

Published 7th August 2015

Citation:

*Brummitt, N.A., ***Bachman, S.P**., Griffiths-Lee, J., Lutz, M., Moat, J.F., Farjon, A., Donaldson, J.S., Hilton-Taylor, C., Meagher, T.R., Albuquerque, S. and Aletrari, E., Andrews, A.K., Atchison, G., Baloch, E., Barlozzini, B., Brunazzi, A., Carretero, J., Celesti, M., Chadburn, H., Cianfoni, E., Cockel, C., Coldwell, V., Concetti, B., Contu, S., Crook, V., Dyson, P., Gardiner, L., Ghanim, N., Greene, H., Groom, A., Harker, R., Hopkins, D., Khela, S., Lakeman-Fraser, P., Lindon, H., Lockwood, H., Loftus, C., Lombrici, D., Lopez-Poveda, L., Lyon, J., Malcolm-Tompkins, P., McGregor, K., Moreno, L., Murray, L., Nazar, K., Power, E., Quiton Tuijtelaars, M., Salter, R., Segrott, R., Thacker, H., Thomas, L.J., Tingvoll, S., Watkinson, G., Wojtaszekova, K., Nic Lughadha, E.M.,2015. *Green plants in the red: a baseline global assessment for the IUCN Sampled Red List Index for Plants*. **PloS ONE**, 10(8), p.e0135152.

*Joint first author

http://dx.doi.org/10.1371/journal.pone.0135152

Authorship statement:

SB and NB are joint first authors. Conceived and designed the experiments: NB SB JM TM ENL. Performed the experiments: NB SB JG-L ML JM TM SA EA EB HC CC V. Coldwell SC V. Crook RH PM-T. Analyzed the data: NB SB JG-L ML JM CH-T. Contributed reagents/materials/analysis tools: NB SB JG-L ML JM AF JD CH-T TM SA EA KA GA EB

BB AB JC MC HC EC CC V. Coldwell BC SC V. Crook PD LG NG HG AG RH DH SK PL-F H. Lindon H. Lockwood CL DL LL-P JL PM-T KMG L. Moreno L. Murray KN EP MQT R. Salter R. Segrott HT LT ST GW KW. Wrote the paper: NB SB JG-L ML JM AF JD CH-T TM ENL.

PLOS | ONE

RESEARCH ARTICLE

Green Plants in the Red: A Baseline Global Assessment for the IUCN Sampled Red List Index for Plants

Neil A. Brummitt[1☯*], Steven P. Bachman[2,3☯], Janine Griffiths-Lee[2], Maiko Lutz[2], Justin F. Moat[2,3], Aljos Farjon[2], John S. Donaldson[4], Craig Hilton-Taylor[5], Thomas R. Meagher[6], Sara Albuquerque[2¤a], Elina Aletrari[1,2,7], A. Kei Andrews[2¤b], Guy Atchison[1¤c], Elisabeth Baloch[2], Barbara Barlozzini[2¤d], Alice Brunazzi[2¤e], Julia Carretero[2], Marco Celesti[2¤f], Helen Chadburn[2], Eduardo Cianfoni[2], Chris Cockel[2¤g], Vanessa Coldwell[2¤h], Benedetta Concetti[2¤i], Sara Contu[1,2], Vicki Crook[2¤j], Philippa Dyson[2¤k], Lauren Gardiner[2], Nadia Ghanim[2], Hannah Greene[1¤l], Alice Groom[2¤m], Ruth Harker[1,2], Della Hopkins[1], Sonia Khela[2¤n], Poppy Lakeman-Fraser[2¤o], Heather Lindon[1,2], Helen Lockwood[2¤p], Christine Loftus[2¤q], Debora Lombrici[2], Lucia Lopez-Poveda[1,2], James Lyon[2], Patricia Malcolm-Tompkins[2], Kirsty McGregor[2¤r], Laura Moreno[2¤s], Linda Murray[2], Keara Nazar[2], Emily Power[2], Mireya Quiton Tuijtelaars[2], Ruth Salter[2], Robert Segrott[2], Hannah Thacker[2¤t], Leighton J. Thomas[2], Sarah Tingvoll[2¤u], Gemma Watkinson[2], Katerina Wojtaszekova[2], Eimear M. Nic Lughadha[2]

1 Natural History Museum, Cromwell Road, South Kensington, London, United Kingdom, **2** Royal Botanic Gardens, Kew, Richmond, Surrey, United Kingdom, **3** School of Geography, University of Nottingham, Nottingham, United Kingdom, **4** South African National Biodiversity Institute, KRC, Private Bag X7, Claremont, South Africa, **5** IUCN Red List Unit, Sheraton House, Castle Park, Cambridge, United Kingdom, **6** School of Biology, Dyers Brae, University of St Andrews, St Andrews, Fife, United Kingdom, **7** King's College London, Strand, London, United Kingdom

☯ These authors contributed equally to this work.
¤a Current address: Universidade de Évora, Palácio do Vimioso, Largo Marquês do Marialva, Évora, Portugal
¤b Current address: Hegelstrasse 7, Tübingen, Germany
¤c Current address: Institute of Systematic Botany, University of Zurich, Zollikerstrasse, Zurich, Switzerland
¤d Current address: SIFitLab (Laboratory of the Italian Society of Herbal Medicine), University of Siena, Via Laterina, Siena, Italy
¤e Current address: Agrobiosciences–Genomics and Crop Science, Scuola Superiore Sant'Anna, Piazza Martiri della Libertà, Pisa, Italy
¤f Current address: Department of Earth and Environmental Sciences, Università degli Studi Milano-Bicocca, Piazza della Scienza, Milano, Italy
¤g Current address: 93 Otho Court, Augustus Close, Brentford, Middlesex, United Kingdom
¤h Current address: Wildfowl and Wetlands Trust, Slimbridge, Gloucestershire, United Kingdom
¤i Current address: ERSAF, Via Oliva, Gargnano (BS), Italy
¤j Current address: TRAFFIC International, Huntingdon Road, Cambridge, United Kingdom
¤k Current address: Zoological Society of London, Regent's Park, London, United Kingdom
¤l Current address: Jacobs, Dundee Street, Edinburgh, United Kingdom
¤m Current address: Royal Society for the Protection of Birds, The Lodge, Potton Road, Sandy, Bedfordshire, United Kingdom
¤n Current address: Cambridgeshire and Peterborough Environmental Records Centre, The Manor House, Broad Street, Great Cambourne, Cambridgeshire, United Kingdom
¤o Current address: Centre for Environmental Policy, Imperial College London, South Kensington, London, United Kingdom
¤p Current address: Artisan Plant Nurseries, Kings Hill Nurseries, Kings Hill Lane, Finham, Coventry, Warwickshire, United Kingdom
¤q Current address: International School of St. Gallen, Höhenweg, St. Gallen, Switzerland
¤r Current address: University Offices, Wellington Square, Oxford, United Kingdom
¤s Current address: WWF España, Gran Vía de San Francisco, Madrid, Spain
¤t Current address: Natural England, Nobel House, Smith Square, London, United Kingdom

Citation: Brummitt NA, Bachman SP, Griffiths-Lee J, Lutz M, Moat JF, Farjon A, et al. (2015) Green Plants in the Red: A Baseline Global Assessment for the IUCN Sampled Red List Index for Plants. PLoS ONE 10(8): e0135152. doi:10.1371/journal.pone.0135152

Editor: Clinton N Jenkins, Instituto de Pesquisas Ecológicas, BRAZIL

Received: December 15, 2014

Accepted: July 18, 2015

Published: August 7, 2015

Data Availability Statement: Sources for samples of species are given in the paper. Specimen data is from publicly available databases such as GBIF (www.gbif.org) or TROPICOS (http://www.tropicos.org/), and are not supplied by us. Additional specimen data from the herbarium at Kew is available online through herbcat (http://apps.kew.org/herbcat/navigator.do) and is also supplied directly to GBIF (http://www.gbif.org/publisher/061b4f20-f241-11da-a328-b8a03c50a862). Specimen data from the Natural History Museum is available from the NHM data portal (data.nhm.ac.uk) and is also supplied directly to GBIF. All assessments submitted to IUCN have either been included on the

Red List website or are in the process of being published by IUCN. The Red List database can be searched from http://www.iucnredlist.org/.

Funding: Funding and support for the first phase of the IUCN Sampled Red List Index for Plants has been provided by the Charles Wolfson Charitable Trust, the Esmée Fairbairn Foundation, Rio Tinto plc., the World Summit on Sustainable Development Implementation Fund of the Department of Environment, Food and Rural Affairs (Defra) of the United Kingdom government and the World Collections Programme, as well as The Natural History Museum and the Royal Botanic Gardens, Kew. The IUCN Red List Unit is generously supported by the Rufford Foundation, the MAVA Foundation and the Environment Agency of Abu Dhabi. Artisan Plant Nurseries did not have any additional role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. Rio Tinto plc. contributed to the funding of digitisation of specimen data and Red List assessment generation during the course of the project, but in no way did this hold any influence over the scientific outputs of this project. The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The funding organisations provided support in the form of salaries for authors, but did not have any additional role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. None of this alters the authors' adherence to PLOS ONE policies on sharing data and materials.

¤u Current address: 12 Stockton Hill, Dawlish, Devon, United Kingdom
* n.brummitt@nhm.ac.uk

Abstract

Plants provide fundamental support systems for life on Earth and are the basis for all terrestrial ecosystems; a decline in plant diversity will be detrimental to all other groups of organisms including humans. Decline in plant diversity has been hard to quantify, due to the huge numbers of known and yet to be discovered species and the lack of an adequate baseline assessment of extinction risk against which to track changes. The biodiversity of many remote parts of the world remains poorly known, and the rate of new assessments of extinction risk for individual plant species approximates the rate at which new plant species are described. Thus the question 'How threatened are plants?' is still very difficult to answer accurately. While completing assessments for each species of plant remains a distant prospect, by assessing a randomly selected sample of species the Sampled Red List Index for Plants gives, for the first time, an accurate view of how threatened plants are across the world. It represents the first key phase of ongoing efforts to monitor the status of the world's plants. More than 20% of plant species assessed are threatened with extinction, and the habitat with the most threatened species is overwhelmingly tropical rain forest, where the greatest threat to plants is anthropogenic habitat conversion, for arable and livestock agriculture, and harvesting of natural resources. Gymnosperms (e.g. conifers and cycads) are the most threatened group, while a third of plant species included in this study have yet to receive an assessment or are so poorly known that we cannot yet ascertain whether they are threatened or not. This study provides a baseline assessment from which trends in the status of plant biodiversity can be measured and periodically reassessed.

Introduction

Responding to global biodiversity targets

At the tenth conference of the parties to the Convention on Biological Diversity (CBD) it was widely agreed that the 2010 Biodiversity Target of a significant reduction in the rate of biodiversity loss [1–2] had not been met [3]. The Parties to the Convention responded to this by proposing a follow-on to the 2010 International Year of Biodiversity, declaring a Decade on Biodiversity and setting 20 new 'Aichi' biodiversity targets to be met by the year 2020 (Decision X/2) [4]. The IUCN Red List of Threatened Species (hereafter referred to as the IUCN Red List) is widely recognised as the most authoritative information source on the extinction risk of species [5–7] and the IUCN Red List Index [8–9], in which genuine changes in IUCN Red List status over time are used to generate an overall index of change, is one of four indicators to measure progress towards Target 12 of the new CBD Strategic Plan (SBSTTA Recommendation XV/1; www.bipindicators.net/globalindicators): that '*the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained*' by 2020.

The IUCN Red List Index was first calculated for the world's birds [3] and has now been applied to other groups of species (e.g. mammals [10], amphibians [11], warm water reef-building corals [12] and freshwater crayfish [13]). The IUCN Sampled Red List Index (SRLI) [14] is an extension of the IUCN Red List Index to larger and less well known groups of organisms that have not been comprehensively assessed; it complements the results for comprehensively assessed groups by representing a broader swathe of global biodiversity but without requiring full assessments for all species in a group. The SRLI contributes to the 'Barometer of Life' [15]: it captures the status of life on earth at a particular moment, and how this changes over time. Baseline values for a Sampled Red List Index have already been calculated for several large but under-assessed groups such as freshwater crabs [16], dragonflies and damselflies [17] and reptiles [18], and work is progressing for butterflies and moths [19] and other groups, providing a better representation of the extinction risk of biodiversity as a whole; from such a baseline, trends can be estimated once these samples have been re-assessed.

Plants are an essential component of biodiversity for which, until now, there has been no global assessment of overall extinction risk. The SRLI for Plants addresses this important gap. It also responds to other global policy mechanisms such as the Global Strategy for Plant Conservation (GSPC) [20], of which Target 2 is a conservation assessment of all plant species, also to be delivered by 2020. Until such time as an assessment of every plant species can be achieved the SRLI for Plants serves as a proxy for overall plant extinction risk and is specifically cited as milestone (d) under GSPC Target 2 (UNEP) [21].

IUCN Red List assessment and extinction risk of plants

Plants provide fundamental support systems for life on Earth and are the basis for all terrestrial ecosystems, and a decline in plant diversity will be detrimental to all other groups of organisms including humans [22–23]. Decline in plant diversity has been hard to quantify, due to the huge numbers of known [24] and unknown [25] species and the lack of an adequate baseline on the extinction risk of species against which to track changes. The IUCN Red List remains the most widely-used and authoritative source of information on threatened plant species worldwide, but the rate at which plant species are described as new to science (more than 2,000 each year–average for last ten years: 2135 [http://www.ipni.org/stats.html]) is nearly equivalent to the number of new IUCN Red List assessments of plants being published each year (approximately 1500 per year since 2001, although the rate is increasing). Significant progress on IUCN Red List assessments has been made for plants at the national and regional level [26–27] and, despite some difficulties with applying IUCN Red List Criteria to global assessments of plants [28–29], to date assessments for 19,738 plants have been published on the IUCN Red List [30].

However, there remains a great need for additional assessments of plant extinction risk [31], and using those plant assessments currently available on the IUCN Red List as a resource to understand the broader status and trends in plant extinction risk is problematic. Firstly, a large proportion of plants already assessed on the IUCN Red List are historic assessments, largely derived from a landmark publication on the extinction risk of tree species [32], which are already in need of re-assessment [33]. Secondly, the current sample of the world's plants on the IUCN Red List gives a biased view of overall extinction risk, mainly because over many years most effort has been focussed on assessing those species that scientists expected to be threatened, due both to the limited resources available for assessments and to a natural tendency to select species considered to be most in need of assessment. The IUCN Red List as it stands thus overestimates the overall proportion of plant species threatened, a bias that is unlikely to diminish until assessments of the majority of plant species are added to the IUCN Red List [34]. The present proportion of plant species listed on the IUCN Red List [30] as threatened is 54%, although this is not reported because IUCN recognise that there is insufficient coverage of assessments across all plant groups to report an accurate percentage of threatened species for plants as a whole. Using a sampled approach [14, 28], the SRLI for Plants tackles this problem by selecting a sample of plant species at random, so that it is representative of plants as a whole. The assessment of several thousand plant species presented here sets the first baseline of global plant extinction risk against which future changes can be measured.

Methods

Species assessed and species selection

From the almost 380,000 known plant species, a random sample of 7,000 species was selected for the SRLI for Plants [28]. Species from five major groups of plants are included (total species numbers for each group follow in square brackets): bryophytes (mosses, liverworts and hornworts) [34,556 species]; pteridophytes (true ferns, lycophytes and allied species) [12,838 species]; gymnosperms (conifers, cycads, gnetophytes and *Ginkgo biloba*) [1,032 species]; monocotyledons (one of the major groups of flowering plants, which includes orchids, bulbous plants, palm trees, aroids and the grass and sedge families) [71,445 species]; and the legume family (peas and beans) [19,874 species]. The legume family was selected as a surrogate for the much larger eudicot clade, for which no authoritative global checklist was available at the time the sample was taken [2008]. The legume family is a large but relatively well-studied family [35] for which a global checklist is available (www.ILDIS.org), and that has been shown to be the angiosperm family which best mirrors overall patterns of global angiosperm diversity [36].

Data sources sampled for each group were: bryophytes: Index of Mosses (http://www.mobot.org/MOBOT/tropicos/most/iom.shtml); pteridophytes: Checklist of World Ferns (http://homepages.caverock.net.nz/~bj/fern/list.htm); gymnosperms: Handbook of the World's Conifers [37], the Cycad Pages (http://plantnet.rbgsyd.nsw.gov.au/PlantNet/cycad/) and the World Checklist of Selected Plant Families (http://apps.kew.org/wcsp/), for *Ephedra* and *Gnetum*; monocots: the Monocot Checklist now incorporated into the World Checklist of Selected Plant Families (http://apps.kew.org/wcsp/); legumes: the International Legume Database and Information Service–ILDIS (http://www.ildis.org/). Taxonomic consistency of all samples taken was subsequently improved by contributions from numerous taxonomic and regional experts, from consulting numerous national checklists, Flora accounts and taxonomic treatments, and through peer-review of the assessments as they were completed. If, at the time of assessment, names taken from the original sample were revealed to be homotypic synonyms of currently accepted taxa (75 cases in the sample of monocot species) and the conservation status was considered to be unaffected, the synonym was replaced in our sample by the accepted name. Heterotypic synonyms (97 monocot species) were also replaced by the accepted name apart from a small number where defaulting to the accepted name was considered likely to produce a different assessment of extinction risk, in which case names were replaced in our sample with other species names selected at random from the relevant list, lest defaulting to the accepted name should introduce a bias towards widespread species. Heterotypic synonyms usually post-date the accepted name to which they are referable, and these more recently described taxa tend to have smaller ranges [38–39].

In order to establish a reasonable sample size to ensure credible taxonomic and geographical breadth in the SRLI samples, an analysis of sample coverage was done using the monocots. The Monocot Checklist (~70,000 species) was successively re-sampled randomly without replacement in increments of 250, and at each increment the Shannon-Weiner and Simpson's indices of diversity [40] were calculated up to a final sample size of 3,000 species; 1,000 iterations per sample size increment were performed (see Supporting Information). Diversity indices measure the number of types in a set of data and how the units are distributed among these types; in this case, units were the number of species and the types are either taxonomic families or geographic region, and this was calculated against the known diversity statistics for the Monocot Checklist as a whole. The objective was to determine the sample size at which a random sample of species yielded a measure of diversity equivalent to either index of diversity for the whole group, and to determine upper and lower bounds of diversity on samples of varying size.

For the major taxonomic groups of plants assessed–except one– 1,500 species were selected randomly without replacement for assessment; the exception is the gymnosperms, of which there are fewer than 1,500 species in the world, so all gymnosperm species are included here, combining assessments by the IUCN SSC Conifer Specialist Group and the IUCN SSC Cycad Specialist Group together with assessments for remaining gymnosperm species carried out by the SRLI for Plants project team.

The sample size of 1,500 species used for the SRLI for Plants is also sufficient to accommodate in-built redundancy in assessments [14] due to taxonomic change/uncertainty or inadequate data being available for some species. Based on simulations using the Red List assessments for all bird species, and confirmed using the Red List assessments for all mammals and all amphibians, it has been determined that to calculate the SRLI with 95% confidence, a threshold number of at least 900 assessments of each sample of 1,500 species (60%) need to be 'data sufficient' and rated as Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN) or Critically Endangered (CR), and not as Data Deficient (DD) [14]. This approach recommended by Baillie et al. [14] and followed here therefore implicitly assumes that the variation in extinction risk for plants will be equivalent to that shown by birds, mammals and amphibians. The threshold of 900 species assessed was met for each of pteridophytes, gymnosperms, monocots and legumes; only preliminary results are so far available for the bryophytes, and results from this group are not currently included in the SRLI for Plants or presented here, except for the preliminary results in Table 1. Apart from Table 1, all other results presented include samples for pteridophytes, monocots and legumes together with the complete assessment of gymnosperms, a combined sample size of 3990 non-DD species assessed. The value of the SRLI for Plants was calculated following the modified formula of Butchart et al. [41].

Table 1. Numbers of species from the combined SRLI for Plants sample of gymnosperms, monocots, legumes and pteridophytes by IUCN Red List Category for each group of plants.

	Monocotyledons	Legumes	Gymnosperms	Pteridophytes	Bryophytes (preliminary results only)	Total	Total excluding bryophytes
CR	32	14	80	18	40	**184**	**144**
EN	55	51	163	46	36	**351**	**315**
VU	71	39	156	91	22	**379**	**357**
Threatened	**158**	**104**	**399**	**155**	**98**	**914**	**816**
lower estimate % threatened	15.46	10.53	39.58	15.95	15.51	**19.77**	**20.45**
best estimate % threatened	**17.59**	**11.43**	**40.38**	**16.01**	**19.60**	**21.44**	**21.68**
upper estimate % threatened	27.59	18.42	41.57	16.36	36.39	**27.52**	**26.12**
NT	67	74	167	55	43	**406**	**363**
LC	677	732	418	758	359	**2944**	**2585**
DD	124	78	20	4	132	**358**	**226**
Subtotal	1026	988	1004	972	632	**4626**	**3990**
NE	478	512	24	528	868	**2410**	
Total	**1500**	**1500**	**1028**	**1500**	**1500**		

doi:10.1371/journal.pone.0135152.t001

Assessment methodology

The extinction risk of each species was assessed using the IUCN Red List Categories and Criteria version 3.1, during the period 2007–2015. [42]. Since the majority of plant species lack any documentation on population sizes or dynamics, for most species the most comprehensive, easily accessible and reliable information on which to base a conservation assessment is the known distribution of that species, utilising Criterion B, although all criteria were considered for each assessment [43]. The best source of this distribution information is the collection of plant specimens held in the world's herbaria [28]. Herbarium specimens provide verifiable records indicating the existence of a species at a given time and place. Historical specimens may play a role in assessments as they can indicate that a decline has occurred, if contemporary surveys reveal that the species is no longer extant at a locality where a historical collection was made. For the purpose of range based measures using Criterion B however, only those specimens considered representative of the present day range should be used and automated tools have been developed to facilitate incorporation of these specimen records into IUCN Red List assessments [44–45]. The herbarium collections at the Royal Botanic Gardens, Kew contain some seven million plant and fungus specimens, and the Natural History Museum, London contains six million plant specimens from all over the world. These were systematically searched for all available specimen information for a given species, and all collections databased and geo-referenced, together with other specimen data available online, such as institutional data portals, e.g. TROPICOS (http://www.mobot.org/MOBOT/tropicos/) or the Global Biodiversity Information Facility (GBIF; www.gbif.org), used with due caution and carefully reviewed and edited to remove duplicate records and erroneous geo-references and where necessary geo-referenced or re-geo-referenced by the project team. These specimen data were combined with information about the species from scientific literature, analysis of the species range using Geographical Information Systems (GIS) together with widely available global datasets such as the Human Footprint Index [46], the World Database on Protected Areas [47] and the Gridded Population of the World [48] and freely available satellite imagery such as in Google Earth, and the expert opinion of scientists who study that species or the area of the world where it is found, to assess the extinction risk for that species and assign an IUCN Red List Category [28].

Species are assessed for the IUCN Red List using any or all of five quantitative criteria A–E [42]. Spatial parameters within the IUCN criteria lend themselves to calculation within a GIS; by collating all known specimens for a species, filtering which of those accurately represent the present distribution, and plotting them on a map it is possible to determine area-based measures such as extent of occurrence (EOO) and area of occupancy (AOO) [28,43,45,49], even for those known from only a handful of specimens [50], and evaluate these metrics against the relevant thresholds for threatened categories [42]. This approach assumes that point distributions adequately capture the extent and occupancy of the species range. For EOO, there is a simple geometric constraint of at least three unique localities required to build the minimum convex polygon (MCP), the metric used to determine EOO [44–45], although sampling intensity should be sufficient such that those three points represent the extent of the species. The estimation of AOO, in particular, is affected by sampling intensity so that it was only used when 'genuine' absence in 2 km x 2 km cells could be inferred, for example a species with a restricted, isolated range on a mountain top that had been well sampled. In extreme cases, even when only a single type specimen is known, it still may be possible to use the AOO measure, depending on the contextual data available [43]. This rapid, automated approach produces a preliminary assessment because further subcriteria must be met to fully justify an IUCN Red List rating [28]. All preliminary assessments were evaluated to determine whether at least two out of three sub-criteria under Criterion B are met, such as a continuing decline in or severe fragmentation of a species' range, so that the assessment can be described as 'full', subject to verification by an independent evaluator. If the additional sub-criteria were not met, the species were either rated as Least Concern, or Near Threatened if the sub-criteria were partially met and were close to the VU thresholds, or DD if there was insufficient information to make a judgement.

Species newly assessed for the SRLI for Plants have associated point data that have either been submitted to, or are in the process of being submitted to IUCN, to verify the area-based calculations and to fulfil the minimum data requirements for IUCN Red List assessments. Species assessed from 2007 onwards by other Red List Authorities or during current assessment programmes were generally not re-assessed, but if a species had previously been assessed and was already listed on the IUCN Red List under older criteria, it was re-assessed under the current IUCN Categories and Criteria (v. 3.1) [42], with a new rating [IUCN Red List Category] as necessary or not. Any species that had previously been assessed under a different (non-IUCN) classification system, such as NatureServe conservation status ranks [51], were re-assessed using IUCN Categories and Criteria (v. 3.1) [42].

Assessments were made available online for peer-review (www.threatenedplants.myspecies.info) and/or sent directly to taxonomic or regional experts or IUCN Red List authorities, and expert workshops held to evaluate individual species ratings. All species assessments were referred to the relevant IUCN Red List Authorities (RLAs) for review as required by the IUCN submissions process. For species not covered by an RLA, these were submitted directly to the IUCN Red List Unit to review or to find alternative experts to conduct the review. Reviewed assessments were forwarded to the IUCN Red List Unit for final checking and publication on the IUCN Red List. By the publication of the 2014.3 IUCN Red List update [30], assessments of 1,009 gymnosperms, 1,005 monocots and 967 legumes have been published, with 25 draft cycad assessments plus 2 in need of updating and 25 further monocot assessments still under review; 972 ferns have been submitted for publication. The remaining species in the sample have yet to receive a full assessment and are listed as Not Evaluated (NE). It is important to emphasize here that the majority of Not Evaluated species have been investigated but put to one side for now as there appeared to be little information on which to base an assessment. These have not been formally rated as Data Deficient, although there is an assumption that most of these will turn out not to be threatened, but these species await further investigation when time allows since NE and DD species do not contribute to the overall SRLI for Plants value. As further data and resources become available these assessments will be carried out and backcast to synchronise with the other SRLI Phase 1 assessments [29].

Proportions of species threatened

The proportion of threatened species for each group was calculated as [Number of threatened / (Total—DD)], where 'threatened' is the number of species assessed as either Vulnerable (VU), Endangered (EN), or Critically Endangered (CR), 'Total' is the total number of species assessed (i.e. excluding species that are Not Evaluated, NE) and DD is the number of species assessed as Data Deficient [10,52]. This gives a 'best estimate' of the percentage of species threatened under IUCN Red List Criteria that effectively assumes that DD species would be assessed with the same proportion threatened–and the same proportions in each of the threatened categories–as the 'data sufficient' species, if there was enough information known about the DD species in order to assess them; the lower estimate is given by [Number of threatened / Total]–thus assuming that no DD species will turn out to be threatened–and the higher estimate by [(Number of threatened + DD) / Total]–thus assuming that all DD species will be assessed as threatened [19,52]. Since many DD species are poorly known as a result of having very small ranges and/or population sizes compared with most data sufficient species, they might be considered more likely to be threatened under IUCN Red List Criteria [53]. However it is not possible to know this with certainty as, by definition, those DD species do not have enough information for them to be assessed.

As the number of species sampled varies between countries, some countries have a very high variance in estimates of the proportion of species threatened, resulting in misleadingly high or low proportions of threatened species for some countries, simply due to low sample size. To account for this, a re-sampling exercise was conducted to establish a threshold number of species sampled per country below which the proportion of species assessed as threatened is likely to be misleading (i.e. where sampling is too low—see Supporting Information and 'SRLI value and geographic patterns' in Results). For sample sizes of one to 250 species, the standard error (SE) of sampled species rated as threatened was determined for 5,000 independent trials and a threshold determined below which the SE is asymptotic (this value is an effective balance between proportions of species that have little support in countries where there are few sampled species assessed, and representing sufficient countries to show global patterns of threatened plant species). This was at a value of less than 0.1 SE, and so proportions of species assessed as threatened or as Data Deficient are not reported for countries with 16 species or fewer.

Results

Diversity statistics

Diversity statistics for random samples of monocot species ((Shannon-Weiner Index and Simpson's Index) stabilise over a narrow range as sample sizes increase beyond 1,250–1,500 species for both species per family (S1 Fig) and species per geographic region (S2 Fig). Random samples at or above these values yield diversity statistics that fall within a narrow range of variability. Thus, we conclude that randomly-selected samples of 1,500 ensure a robust coverage of the whole of the monocotyledons both taxonomically and geographically. This sample size is corroborated by modelling done by Baillie et al. (14) to test the repeatability of the SRLI for different sample sizes. For the following results presented by region and by habitat, and the figures summarising threats to plant species and proportions of threatened species by country, all four plant groups assessed have been analysed together (3990 non-DD species in total) rather than separately, so that the set of species within each region, habitat or country is large enough for there to be confidence in these results.

Proportion of threatened plant species

Overall, more than one in five (almost 22% using the 'best' estimate of the proportion of threatened species) of plant species assessed are threatened with extinction, while close to one in three (30%) of all plant species assessed of elevated conservation concern, being either threatened or Near Threatened (that is, they are close to meeting the criteria for one of the threatened categories and are likely to become threatened if no steps are taken to halt their decline). The proportion of species threatened varies between the four groups assessed to date (Table 1), with only 11% of species estimated to be threatened for legumes, 16% for pteridophytes, 18% for monocots and 40% for gymnosperms; however, for each of these major groups many more species (between 7% and 17%) are classified as Near Threatened, and up to 50% of species are either threatened or Near Threatened in the case of gymnosperms (Table 1). A very high proportion of species, just over a third (34%), remains classified as either Data Deficient (6% of species assessed) or Not Evaluated (28% of the original sample), meaning not enough is

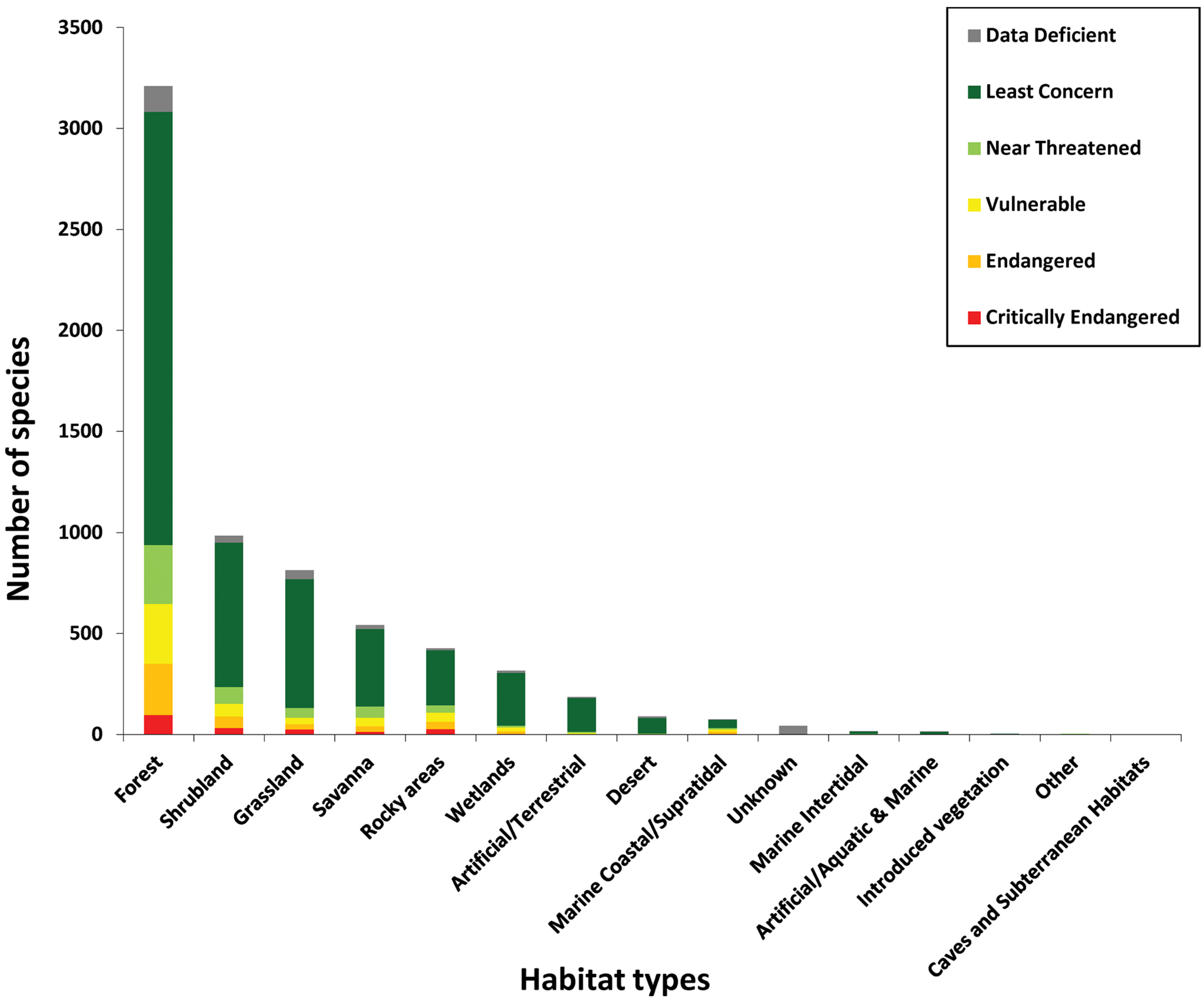


Fig 1. Numbers of species from the combined SRLI for Plants sample of gymnosperms, monocots, legumes and pteridophytes in each IUCN Red List Category by habitat.

doi:10.1371/journal.pone.0135152.g001

currently known about them to complete an IUCN Red List assessment (DD) or that an assessment cannot yet be completed (NE). Almost two-thirds (65%) of plant species assessed for this study have been assessed as Least Concern and have a low probability of extinction (Table 1).

The species included in this study are spread across major plant groups, habitats and regions of the world; because of the random nature of the sample, the numbers of species are in proportion to the plant diversity within each habitat or region. The species assessed can be divided into the habitats (Fig 1) and realms (Table 2) of the world in which they are known to occur. Discounting Antarctica and surrounding sub-Antarctic islands, which only have five species assessed for the SRLI for Plants, the region of the world with the greatest threats affecting its plant diversity is the Neotropics, with 23% of assessed species threatened, with tropical Africa (22%) and tropical Asia (21%) only just behind. Australasia, with a very large number and high proportion of endemic species, also has a high proportion of assessed species threatened (18%), while the islands of Oceania have 16% threatened. Lower proportions of the flora are

Table 2. Numbers of species from the combined SRLI for Plants sample of gymnosperms, monocots, legumes and pteridophytes in each IUCN Red List Category by realm.

	Afrotropical	Antarctic	Australasian	Indomalayan	Nearctic	Neotropical	Oceanian	Palearctic
CR	33	1	11	21	8	59	2	10
EN	50	0	44	65	19	108	6	29
VU	65	0	68	77	13	109	3	41
NT	57	0	82	71	34	95	2	46
LC	459	4	474	534	324	854	55	530
DD	49	0	26	54	1	55	1	48
Total # species	**713**	**5**	**705**	**822**	**399**	**1280**	**69**	**704**
Total threatened	**148**	**1**	**123**	**163**	**40**	**276**	**11**	**80**
Lower estimate % threatened	**20.76**	**20.00**	**17.45**	**19.83**	**10.03**	**21.56**	**15.94**	**11.36**
Best estimate % threatened	**22.29**	**20.00**	**18.11**	**21.22**	**10.05**	**22.53**	**16.18**	**12.20**
Upper estimate % threatened	**27.63**	**20.00**	**21.13**	**26.40**	**10.28**	**25.86**	**17.39**	**18.18**

doi:10.1371/journal.pone.0135152.t002

threatened in temperate Eurasia (12%) or North America (10%) in this study (Table 2). The habitat with the greatest number of threatened species is clearly forest, with 79% of threatened species found in this habitat, followed by 19% of threatened species in shrubland, 13% in rocky outcrops, 10% in savanna and also 10% in grassland (Fig 1; percentages do not sum to 100% as some species occur in more than one habitat). Habitats with the greatest proportions of threatened species are all areas undergoing rapid conversion to agriculture. Habitats that contain the smallest proportions of threatened species, such as deserts and wetlands, are, perhaps unsurprisingly, areas least suitable for conversion to agriculture.

The impact of humans on plant diversity

Most of the threatened species identified in this study are restricted to very small areas and are threatened by habitat conversion (see also [31]), with 'Biological Resource Use' and 'Agriculture, Aquaculture' together accounting for 50% of identified threats to plants (Fig 2). Within each of these broad classes, some key threats stand out. Arable farming affects 60% of threatened species, while livestock farming affects 47%, logging affects 38%, targeted harvesting affects 25% and fires (natural or man-made) also affect 25% of threatened species.

SRLI value and geographic patterns

The baseline value of the SRLI for Plants is 0.86 (Fig 3), almost equal to that for mammals (0.85); compared with the other completely-assessed vertebrate groups, plants are less threatened than amphibians (0.74) but are more threatened than birds (0.92). Numbers of species assessed per country are presented in Fig 4A, proportions of species assessed as threatened per country are given in Fig 4B and gaps in our current knowledge of plant extinction risk given in Fig 4C. The full number of assessed species per country is shown in Fig 4A, but for Fig 4B and 4C data were only displayed for countries with 17 or more species assessed as non-Not Evaluated, as determined from simulations (S3 Fig). Particular gaps in knowledge are evident in Brazil, in Angola and Chad in Africa, and in southern Asia from Iran and through SE. Asia to Papua New Guinea (Fig 4C). A country-level funnel plot of the proportion of species that are threatened against number of species (Fig 5) also shows those countries with especially high proportions of threatened species, with several of the 'megadiverse' [54] countries (Madagascar, South Africa, Mexico, Brazil, Australia and China, and also Viet Nam and Malaysia, along with New Caledonia and Reúnion) having disproportionately high numbers of threatened species in this sample.

Discussion

From our analysis of the SRLI for Plants, it is possible to say for the first time which plants from the sample are at greater risk of extinction, where and why. The sample of species assessed for this project is broadly representative of the world's plants as a whole, and collectively there are sufficient species assessed for it to also be representative of some broad-scale geographical patterns. Previous work [14] determined an appropriate sample size for the SRLI on purely statistical grounds, and assessed the taxonomic and geographic coverage of samples retrospectively, whereas here the appropriate sample size has been determined independently of any single sample of species. By combining the results for each of the major plant groups together a robust and more detailed picture of the threats facing plant diversity emerges; these results are based on many thousands of assessments of individual species that in turn are based on hundreds of thousands of individual plant records.

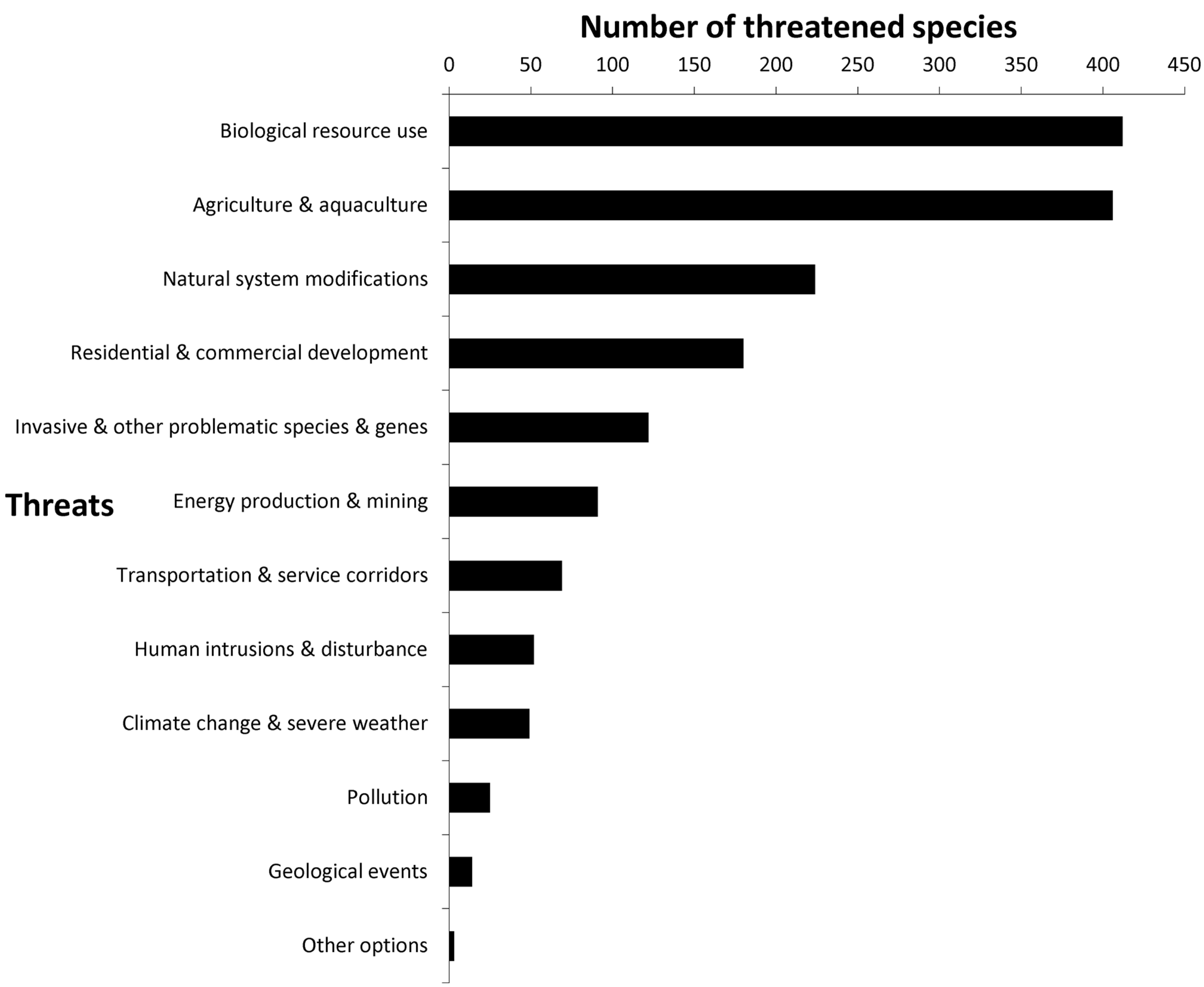


Fig 2. Threats to species from the combined SRLI for Plants sample of gymnosperms, monocots, legumes and pteridophytes, by number of plant species threatened. Individual species may be affected by more than one threat.

doi:10.1371/journal.pone.0135152.g002

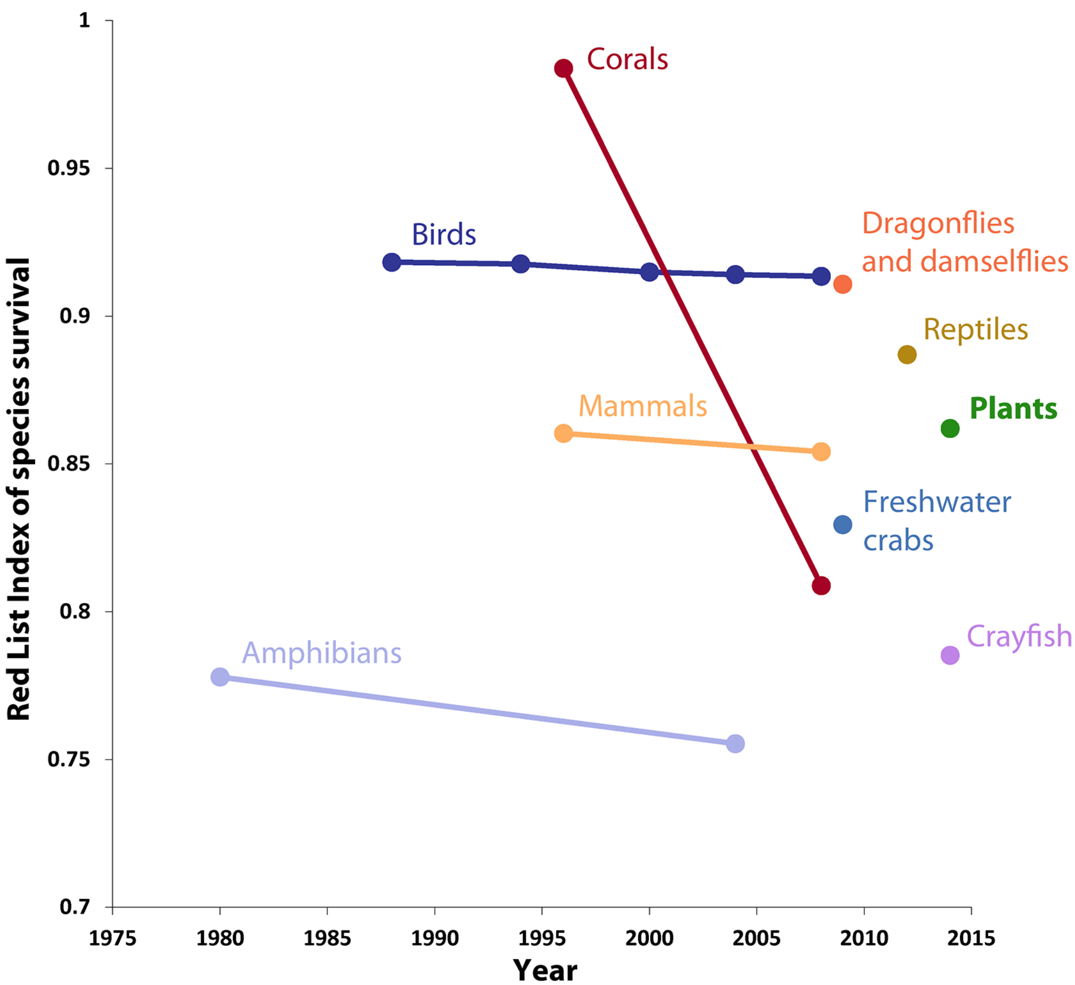


Fig 3. Red List Indices for birds, mammals, amphibians and corals (source: IUCN), with baseline values for crayfish [13], freshwater crabs [16], dragonflies & damselflies [17], reptiles [19] and plants (this study). Values for crayfish, freshwater crabs, dragonflies and damselflies, reptiles and plants are based on a sampled approach.

doi:10.1371/journal.pone.0135152.g003

The threatened plants

Species from tropical regions are, in general, about twice as likely to be threatened as are species from temperate regions (21.22%–22.53% species threatened for tropical regions, 10.05%–12.2% species threatened in north temperate regions; Table 2); this may be partly attributable to temperate species having naturally larger ranges [55] and thus being less severely affected by localised threats. Other factors contributing to the marked contrast in proportions of threatened species between temperate and tropical regions may include the greater rate of land-use change occurring in the tropics, and the fact that in temperate areas such as Europe much of the change in land use and habitat cover has occurred a long time ago (i.e. more than 3 generations ago for most plant species) and native forest has been replaced by stable grassland or heathland communities, hence the species left have depleted populations but are no longer declining. In tropical regions there is typically much less detailed knowledge of the distribution of rare species, and also many more naturally rare species occur in the tropics across a greater diversity of habitats [56]. With increasing levels of habitat loss, the extinction of locally endemic species is highly likely.

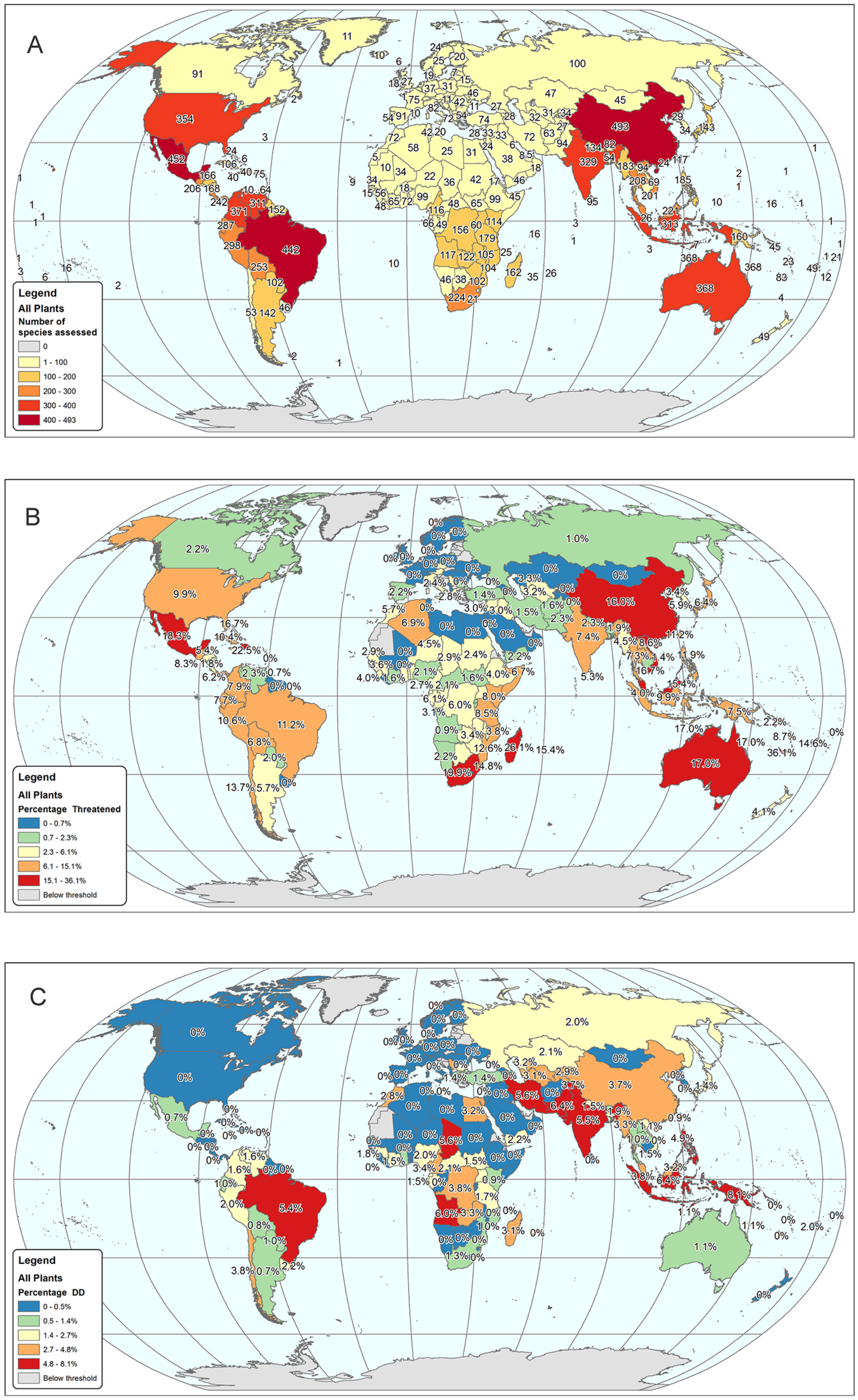


Fig 4. Global map of average extinction risk of species per country from the combined SRLI for Plants sample of gymnosperms, monocots, legumes and pteridophytes. A. Number of species assessed per country. B. Percentage of assessed species that are threatened per country. C. Percentage of assessed species that are Data Deficient per country.

doi:10.1371/journal.pone.0135152.g004

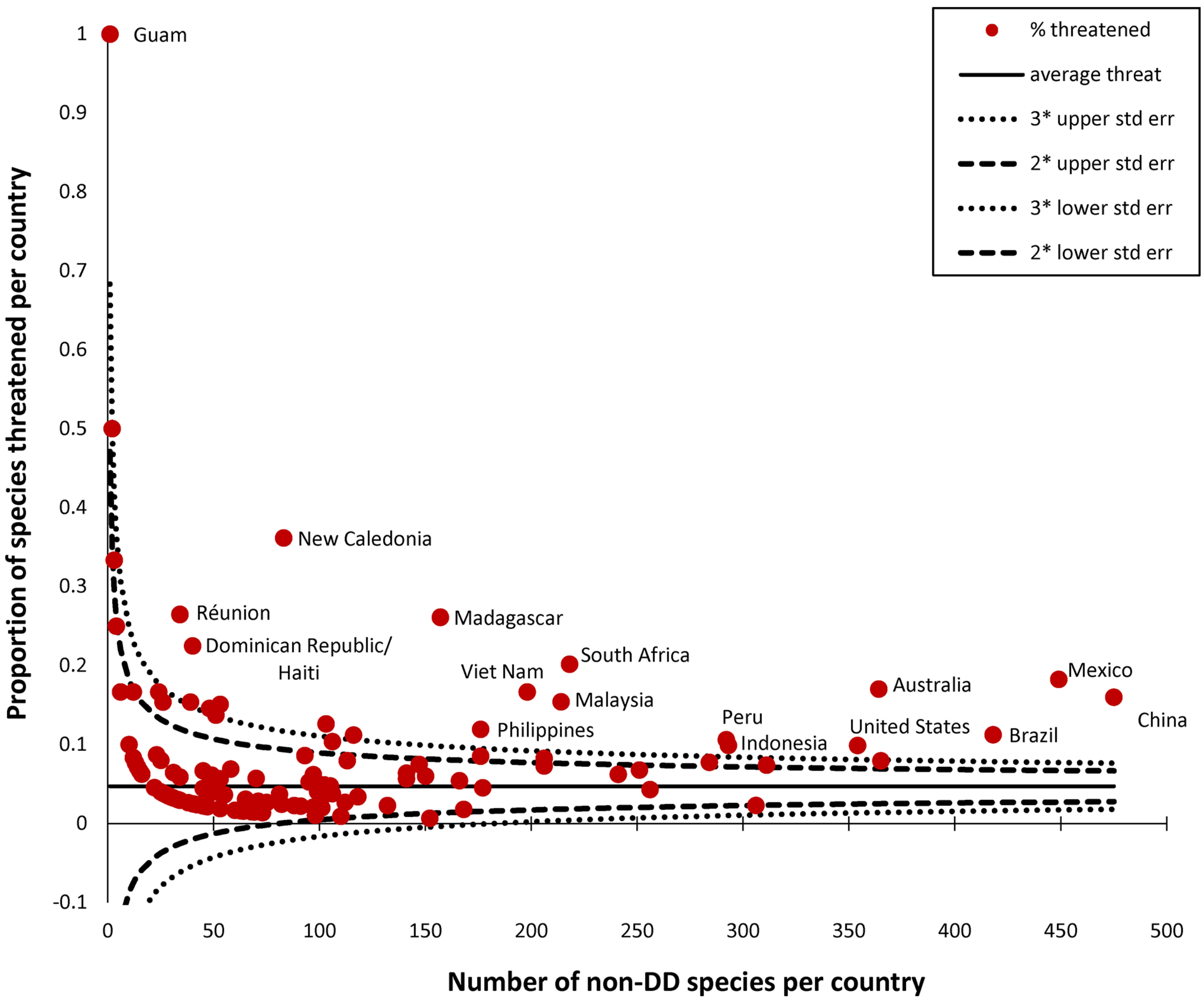


Fig 5. Funnel plot of degree of threat as a proportion of species assessed per country for the combined SRLI for Plants sample of gymnosperms, monocots, legumes and pteridophytes.

doi:10.1371/journal.pone.0135152.g005

Non-threatened species

Almost two-thirds of plant species assessed for this study are classified as Least Concern. However, in many cases there has already been a reduction in the quantity or quality of natural habitat across the ranges of these species, although the range or population of these species have not yet declined sufficiently fast or to sufficiently low values to meet the thresholds set by IUCN for a threatened category, in some cases because the species is known to occur within effectively managed protected areas. In addition, some are naturally small-ranged, but are not currently undergoing range or population decline despite falling under the IUCN EOO threshold for Vulnerable. Conversely, as we have taken a randomly-selected sample representative of all plants more broadly, a few species in this study are aggressive colonisers with extremely widespread distributions, for example bracken (*Pteridium aquilinum*). The high proportion of 'data insufficient' ratings–either Not Evaluated (those that at first glance did not appear to have enough information on which to base an assessment) and those formally assessed as Data

Deficient–in the sample of species tells a story in its own right: about as many new plant species are described each year as are published on the IUCN Red List, and the biodiversity of many parts of the world, especially in inaccessible regions of the tropics, still remains largely unexplored. Many species have received no further attention since they were first described many decades ago, and much of the baseline research on what plant species occur where in the world is still in progress.

Legumes as proxies for broader angiosperm patterns

The SRLI for Plants is calculated giving equal weight to each taxonomic group included in the index, following Baillie et al. [14]. However, if the value of the SRLI plants were to be re-calculated (weighted) to reflect the total number of species for each taxonomic group of plants, in their current proportions between IUCN Red List Categories (i.e. the 'best' estimate of proportions threatened, across all species), still using the legumes as a proxy for all angiosperms other than monocots, then the SRLI value would increase to 0.91, or 1 in 7 plant species (results not shown). Weighting each group equally emphasizes an equivalent degree of knowledge of species extinction risk, whereas weighting each group in proportion to its number of species effectively gives greater weight to groups that are less well studied and less valued by the public [14], which is arguably less comprehensible and less useful to policy and decision makers. Whether legumes are a good proxy for the extinction risk of other non-monocot angiosperms can only be established with certainty when a sample including other families has been assessed. However, additional studies further suggest that legume diversity may serve as a proxy for total plant diversity in biogeographical and ecological analyses [57–61]. Resources permitting, a broader sample of non-monocot angiosperms will be included in the next round of assessments for the SRLI for Plants.

Goodhart's Law

The value of the IUCN Sampled Red List Index for Plants has been estimated from robust assessments of several thousand species using available information, yet this represents only a very small proportion of the total number of plants. What ensures that the value of the SRLI for Plants truly represents the status of the rest of plant diversity? Targeted conservation actions aimed only at SRLI species could disproportionately influence the value of the Index, suggesting a healthier picture for global plant extinction risk than is the case for non-SRLI plant species–the vast majority of species. The imposition of targets measuring performance often precipitates changes in the behaviour of those responsible for the performance of the system–a phenomenon described by Goodhart's Law [62]. What is to stop the small selection of plant species becoming the target of specific conservation actions designed merely to improve the status of the species sampled, and hence the reading of the Index, with no commensurate improvement in the status of other species?

While acknowledging that action targeted disproportionately on species in the SRLI sample may risk incorrect inferences from future readings of the Index, we consider that the absolute rather than relative number of plant species selected and assessed to date, the range of taxonomic groups and the global geographical and ecological coverage achieved all mitigate this risk. Moreover, the current (non-Sampled) Red List Index includes assessments for over 20,000 and species of birds, mammals, amphibians and corals, and the SRLI as a whole, once samples are re-assessed and incorporated into a combined index, will include not only plants but assessments of tens of thousands of species representing many more groups of organisms [14,16–19] It is hard to see how a positive change in the Index as a whole would not genuinely represent a positive improvement in the status of global biodiversity. Furthermore, the assessments for plant species are often based on use of criterion B, as discussed above, which requires that two out of three subcriteria need to be met, one of which relates to a decline in size and structure of species' range or quality of habitat. This criterion (B1 and/or B2) has been used for 59% of threatened plant species assessed for the SRLI for Plants [29]. For species to be assessed as threatened under criterion B, two out of three subcriteria also need to be fulfilled; in the majority of cases this is a severely fragmented distribution or small number of locations (subcriterion a), together with a recent and ongoing decline in either the range of the species or in the quality or the extent of its habitat (subcriterion b iii). This means that for the majority of threatened SRLI plant species, a positive change in their IUCN Red List status may also mean an improved situation for non-SRLI species found within the range or the same habitat as those SRLI species receiving careful attention.

Plants in comparison with other organisms

The SRLI is scaled between 1 and 0, where a value of 1 would indicate that every species included in the Index was Least Concern, whereas a value of zero would indicate that every species in the index had gone extinct [41]. The value for all plant groups included in the SRLI for Plants [3990 species] is 0.86, showing that overall, plants have a comparable level of extinction risk as do mammals [0.85], are much more threatened than are birds [0.91], but are much less threatened than are amphibians [0.76] (c.f. [52]). For other taxonomic groups from which samples have been assessed, SRLI values range from 0.91 (dragonflies and damselflies) to 0.79 (freshwater crayfish). Warm water reef-building corals show the steepest decline in extinction risk of any completely assessed group, largely due to the impacts of climate change on ocean acidification, ocean warming and reef formation, and to local habitat destruction caused by over-fishing of reef-dwelling fish [12]. Countries with a high proportion of threatened plant species are those 'megadiverse' countries [54] whose floras constitute a confluence of many different floristic elements [63]. These same countries are also areas of high vertebrate diversity and threat [64–65]. Therefore, the future of plant diversity depends on the conservation actions taken in the next few years in combination with efforts to conserve the world's animal species [56,66].

Life depends on plants–safeguarding our future

The results from the SRLI for Plants graphically show the impact of humans on the state and fate of plant diversity. Most threatened species are found in the tropics, where the greatest diversity of plants is [39], with 21–23% threatened compared to 10–12% threatened in temperate regions (Table 2). Oceanic islands have fewer species but these are often found nowhere else, and are more likely to be threatened, especially by the introduction of invasive species [67]. Threatened species identified in this study have mostly (59%) been assessed under Criterion B, and are predominantly narrow endemics threatened by habitat conversion, or species naturally confined to very restricted areas [29] 'such that they are prone to the effects of human activities or stochastic events within a very short time period in an uncertain future' [42] and are thus liable to become Critically Endangered or Extinct in a very short time period.

The habitat with the greatest number of threatened species is tropical rain forest, where 79% of threatened species are found. Changes in habitat cover can be clearly seen from satellite images, and many localities where specimens have been collected within recent years would now be unrecognisable. The overwhelming threat affecting the future of plant species is the continued destruction of natural habitats and their ongoing degradation or conversion to agriculture. Areas least suitable for conversion to agriculture, such as wetlands and deserts, contain the smallest proportions of threatened plant species, with 3% and less than 1% of threatened species, respectively. Land use change from natural to man-made habitats is the major driver of changes in the provision of ecosystem services, and the Millennium Ecosystem Assessment has forecast that 10–20% of current grassland and forested land may be lost between now and 2050, mainly due to the further expansion of agriculture [68]. This fragments the ranges of already-threatened species further, isolating or eliminating populations and preventing their natural dispersal and ability to reproduce. Plants are the primary producers for all terrestrial and almost all aquatic ecosystems. They have roles of fundamental importance in providing food, shelter and building materials for humans as well as for many animal species, for regulating climate, providing supporting ecosystem services such as soil formation, preventing soil erosion and desertification, filtering fresh water, nutrient cycling, photosynthesis and for structuring habitats. More than one in five plant species assessed is already threatened with extinction, even without considering the threats associated with a changing climate. A trait-based assessment of the vulnerability of species of other taxonomic groups to climate change has shown large numbers of species that are not currently threatened but which are highly vulnerable to climate change impacts (potentially as many as 41% of bird species, 29% of amphibian species and 22% of reef-forming corals [69]). If the same patterns hold true for plants, the number of plant species of conservation concern is likely to rise sharply in the coming decades. The current rate of loss of tropical forest accounts for 20% of global carbon emissions, which means that taking the necessary steps to reduce biodiversity loss will also make a significant contribution to mitigating the impact of climate change. This would be a win-win situation for our own species and countless thousands of others.

Phase II of the SRLI for Plants: re-assessing the species

All assessments carried out for this project are underpinned by accurate and reliable information on where and when a species has been collected, with an auditable data trail to the source data, and are validated by the opinion of taxonomic or regional experts and double-checked by the IUCN Red List Unit. However, most are based on knowledge of the species' range and habitats and information about the current vegetation cover within that area: in common with almost all plant species, few have been recently surveyed in their natural habitat. Doing so would greatly enhance the existing assessments by enabling the use of a wider range of the IUCN Red List Criteria and improving the rigour of ratings that are generally based on a remote analysis of species ranges from recent and historical herbarium specimen data. Using the associated specimen data for each assessment, hotspots of threatened plant species diversity can be identified at higher spatial resolution, and targeted field expeditions to survey these threatened species in the wild will concentrate in these areas, providing a focussed framework for conservation actions and ensuring that resources are used effectively and where they are most needed [29,70–73].

In order for changes in the value of the IUCN Red List Index to be seen, changes in the status of each species need to be detected [8–9], and so these species need to be regularly surveyed. The aim is for each species to be re-assessed every five years, and the Index re-calculated; species which have undergone a genuine change in their extinction risk then drive the change in the value of the Index. If an international network of scientists and relevant institutions such as botanic gardens and natural history museums can be mobilised, and monitoring schemes established or expanded at national scales [26] then the baseline presented here can be built on to accurately monitor future trends in the status of plant diversity worldwide. The use of web platforms to harvest and collate photographic records and population survey data (e.g. www.inaturalist.org), the analysis of long-term Earth Observation data [74] to better understand declines in populations and the harnessing of data from citizen science-type initiatives [75] are all likely to underpin the next phase of this work [29].

Conclusion

This initial phase of the SRLI for Plants marks the first step towards monitoring global extinction risk in plant species. It provides the baseline against which future changes can be tracked–and it shows clearly that urgent action is needed if we are to avoid losing one in five plant species. Subsequent assessments of this sample will provide a trend in plant extinction risk, indicating whether extinction of threatened species has been prevented and whether the status of those species most in decline has been improved, directly responding to Aichi Target 12. In addition, being the first representative assessment of extinction risk of plants it also provides the first direct response to a milestone of the second target of the Global Strategy for Plant Conservation (GSPC). We hope the methods and techniques uses in this study, as well as the headline results, will act as a stimulus to further plant extinction risk assessment activity and help galvanise and mobilise the international network of local botanists and botanic gardens to establish the SRLI for Plants as a broad-based monitoring scheme. The world cannot afford to lose a quarter of its plant species; we must all work together to conserve what we have.

Supporting Information

S1 Fig. Diversity statistics based on species numbers of monocots distributed across families. Minimum and maximum estimates obtained across different sample sizes are shown for Shannon-Weiner (squares) and Simpson (diamonds) diversity indices; lines within the bounds represent diversity estimates for monocots as a whole.
(DOC)

S2 Fig. Diversity statistics based on species numbers of monocots distributed across geographic regions. Minimum and maximum estimates obtained across different sample sizes are shown for Shannon-Weiner (squares) and Simpson (diamonds) diversity indices; lines within the bounds represent diversity estimates for monocots as a whole.
(DOC)

S3 Fig. Plot of standard error against number of species sampled for 5,000 random simulations. The threshold value used for showing countries on the maps in Fig 4 (17 species) is highlighted in red.
(DOCX)

Acknowledgments

We are grateful to Dr. Alan Paton for advice and support and to A. Bell, R. Boccardo, F. Danmeri, A. Dennis, A. Devine, K. Garrett, S. Jenkins, C. McCartney, F. Ramond-Monnier, W. Saunders and B. Turpin for additional databasing, geo-referencing and assessment activities. We thank the IUCN Red List Secretariat who support the delivery of the IUCN Red List and in particular the staff of the IUCN Red List Unit in Cambridge and all Plant Specialist groups and Plant Red List Authorities who contributed to the production or review of assessments included in this analysis, and would like to extend these sincere thanks to the many experts who contributed their time and knowledge to the assessment review process. Dr. Bob Magill (Missouri Botanical Garden, USA), kindly provided a randomly-selected sample of 1500 bryophyte species together with synonymy and distribution records from W^{3}MOST (http://www.mobot.org/MOBOT/tropicos/most/iom.shtml); Dr. Pete Winfield did the same for legume species from the International Legume Database and Information Service (ILDIS; http://www.ildis.org/). Volunteers at Missouri Botanical Garden also databased and georeferenced specimen data for the sample of bryophyte species from their collections. We also thank Lucas Joppa, Pedro Cardoso and one anonymous reviewer for comments on the manuscript. Funding and support for the first phase of the IUCN Sampled Red List Index for Plants has been generously provided by the Charles Wolfson Charitable Trust, the Esmée Fairbairn Foundation, Rio Tinto plc., the World Summit on Sustainable Development Implementation Fund of the Department of Environment, Food and Rural Affairs (Defra) of the UK government and the World Collections Programme, as well as The Natural History Museum and the Royal Botanic Gardens, Kew, to all of whom we are extremely grateful. The IUCN Red List Unit is generously supported by the Rufford Foundation, the MAVA Foundation and the Environment Agency of Abu Dhabi.

Author Contributions

Conceived and designed the experiments: NB SB JM TM ENL. Performed the experiments: NB SB JG-L ML JM TM SA EA EB HC CC V. Coldwell SC V. Crook RH PM-T. Analyzed the data: NB SB JG-L ML JM CH-T. Contributed reagents/materials/analysis tools: NB SB JG-L ML JM AF JD CH-T TM SA EA KA GA EB BB AB JC MC HC EC CC V. Coldwell BC SC V. Crook PD LG NG HG AG RH DH SK PL-F H. Lindon H. Lockwood CL DL LL-P JL PM-T KMG L. Moreno L. Murray KN EP MQT R. Salter R. Segrott HT LT ST GW KW. Wrote the paper: NB SB JG-L ML JM AF JD CH-T TM ENL.

References

1. Balmford AL, Bennun B, ten Brink D, Cooper IM, Côté P, Crane, et al. The convention on biological diversity's 2010 Target. Science 2005; 307: 212–213. PMID: 15653489
2. Walpole M, Almond REA, Besançon C, Butchart SHM, Campbell-Lendrum D, Carr GM, et al. Tracking progress toward the 2010 Biodiversity target and beyond. Science 2009; 325: 1503–1504. doi: 10.1126/science.1175466 PMID: 19762630
3. Butchart SHM, Walpole M, Collen B, van Strien A, Scharlemann JWP, Almond REA, et al. Global biodiversity: indicators of recent declines. Science 2010; 328: 1164–1168. doi: 10.1126/science.1187512 PMID: 20430971
4. Tittensor DP, Walpole M, Hill SLL, Boyce DG, Britten GL, Burgess ND, et al. A mid-term analysis of progress toward international biodiversity targets. Science 2014; 346(6206): 241–244. doi: 10.1126/science.1257484 PMID: 25278504
5. Lamoreux J, Akçakaya HR, Bennun LA, Collar NJ, Boitani L, Brackett D, et al. Value of the IUCN Red List. Trends in Ecology and Evolution 2003; 18: 214–215.
6. Rodrigues ASL, Pilgrim JD, Lamoreux JF, Hoffmann M, Brooks TM. The value of the IUCN Red List for conservation. Trends in Ecology and Evolution 2006; 21: 71–76. PMID: 16701477
7. Mace GM, Collar NJ, Gaston KJ, Hilton-Taylor C, Akçakaya HR, Leader-Williams N, et al. Quantification of extinction risk: IUCN's system for classifying threatened species. Conservation Biology 2008; 22: 1424–1442. doi: 10.1111/j.1523-1739.2008.01044.x PMID: 18847444
8. Butchart SHM, Stattersfield AJ, Bennun LA, Shutes SM, Akcakaya HR, Baillie JEM, et al. Measuring global trends in the status of biodiversity: Red List Indices for birds. PLoS Biology 2004; 2: 2294–2304.
9. Butchart SHM, Stattersfield AJ, Baillie JEM, Bennun LA, Stuart SN, Akçakaya HR, et al. Using Red List Indices to measure progress towards the 2010 target and beyond. Philosophical Transactions of the Royal Society of London B: Biological series 2005; 360: 359–372.
10. Schipper J, Lamoreux J, Rodrigues ASL, Stuart SN, Temple HJ, Baillie JEM, et al. The status of the world's land and marine mammals: diversity, threat, and knowledge. Science 2008; 322: 225–230. doi: 10.1126/science.1165115 PMID: 18845749
11. Stuart SN, Chanson JS, Cox NA, Young BE, Rodrigues ASL, Fischman DL, et al. Status and trends of amphibian declines and extinctions worldwide. Science 2004; 306: 1783–1786. PMID: 15486254

12. Carpenter KE, Abrar M, Aeby G, Aronson RB, Banks SA, Bruckner A, et al. One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 2008; 321: 560–563. doi: 10.1126/science.1159196 PMID: 18653892
13. Richman NI, Böhm M, Adams SB, Alvarez F, Bergey EA, Bunn JJS, et al. Multiple drivers of decline in the global status of freshwater crayfish. Philosophical Transactions of the Royal Society of London, Series B Biological Sciences (in press).
14. Baillie JEM, Collen B, Amin R, Akçakaya HR, Butchart SHM, Brummitt NA, et al. Toward monitoring global biodiversity. Conservation Letters 2008; 1: 18–26.
15. Stuart SN, Wilson EO, McNeely JA, Mittermeier RA, Rodríguez JP. The Barometer of Life. Science 2010; 328: 117.
16. Cumberlidge N, Ng PKL, Yeo DCJ, Magalhaes C, Campos MR, Alvarez F, et al. 2009. Freshwater crabs and the biodiversity crisis: importance, threats, status, and conservation challenges. Biological Conservation 142: 1665–1673.
17. Clausnitzer V, Kalkman VJ, Ram M, Collen B, Baillie JEM, Bedjanič M, et al. Odonata enter the biodiversity crisis debate: The first global assessment of an insect group. Biological Conservation 2009; 142: 1864–1869.
18. Böhm M, Collen B, Baillie JRM, Bowles P, Chanson J, Cox N, et al. The conservation status of the world's reptiles. Biological Conservation 2012; 157: 372–385.
19. Lewis OT, Senior MJM. Assessing conservation status and trends for the world's butterflies: the Sampled Red List Index approach. Journal of Insect Conservation 2011; 15: 121–128.
20. UNEP. Conference of Parties to the Convention on Biological Diversity. Decision X/17. Consolidated update of the Global Strategy for Plant Conservation 2011–2020; 2010a. Available: http://www.cbd.int/decision/cop/?id=12283
21. UNEP. Conference of Parties to the Convention on Biological Diversity. Global Strategy for Plant Conservation technical rationale, justification for updating and suggested milestones and indicators; 2010b. Available: http://www.cbd.int/gspc/technical.shtml
22. Díaz S, Fargione J, Chapin FS III, Tilman D. Biodiversity loss threatens human well-being. PLoS Biology 2007; 4(8): e277.
23. Pereira HM, Leadley PW, Proença V, Alkemade R, Scharlemann JPW, Fernandez-Manjarres JF, et al. Scenarios for Global Biodiversity in the 21st Century. Science 2010a; 330(6010): 1496–1501. doi: 10.1126/science.1196624 PMID: 20978282
24. Paton AJ, Brummitt NA, Govaerts R, Harman K, Hinchcliffe S, Allkin R, et al. A working list of all known plant species–progress and prospects towards Target 1 of the Global Strategy for Plant Conservation. Taxon 2008; 57(2): 602–611.
25. Joppa LN, Roberts DL, Pimm SL. How many species of flowering plants are there? Proceedings of the Royal Society series B, Biological Sciences 2011a; 278: 554–559.
26. Zamin TJ, Baillie JEM, Miller RM, Rodriguez JP, Ardid A, Collen B. National Red Listing beyond the 2010 Target. Conservation Biology 2010; 24(4): 1012–1020. doi: 10.1111/j.1523-1739.2010.01492.x PMID: 20337689
27. Raimondo DC, von Staden L, Donaldson JS. Lessons from the conservation assessment of the South African megaflora. Annals of the Missouri Botanical Garden 2013; 99(2): 221–230.
28. Brummitt NA, Bachman SP, Moat JF. Applications of the IUCN Red List: towards a global barometer for plant diversity. Endangered Species Research 2008; 6: 127–135.
29. Brummitt NA, Bachman SP, Aletrari E, Chadburn H, Griffiths J, Lutz M, et al. The Sampled Red List Index for Plants, Phase II: ground-truthing specimen-based conservation assessments. Philosophical Transactions of the Royal Society series B, Biological Sciences (in press)
30. IUCN. IUCN Red List version 2014.3: Table 1; 2014a. Available: http://cmsdocs.s3.amazonaws.com/summarystats/2014_3_Summary_Stats_Page_Documents/2014_3_RL_Stats_Table1.pdf
31. Giam XL, Sodhi NS, Brook BW, Tan HTW, Bradshaw CJA. Relative need for conservation assessments of vascular plant species among ecoregions. Journal of Biogeography 2011; 38(1): 55–68.
32. Oldfield S, Lusty C, MacKinven A. The World List of Threatened Trees. World Conservation Press, Cambridge, UK; 1998.
33. Newton AC, Oldfield S. Red Listing the world's tree species: a review of recent progress. Endangered Species Research 2008; 6: 137–147.
34. Hilton-Taylor C, Pollock CM, Chanson JS, Butchart SHM, Oldfield TEE, Katariya V. State of the world's species. In: Vié J.-C., Hilton-Taylor C. and Stuart S.N. (eds.) Wildlife in a Changing World—An Analysis of the 2008 IUCN Red List of Threatened Species, IUCN, Gland, Switzerland; 2008. pp. 15–41.

35. Lewis GP, Schrire BD, Mackinder B, Lock JM (editors). Legumes of the World. Royal Botanic Gardens, Kew, UK; 2005.
36. Nic Lughadha E, Baillie J, Barthlott W, Brummitt NA, Cheek MR, Farjon A, et al. Measuring the fate of plant diversity: towards a foundation for future monitoring and opportunities for urgent action. Philosophical Transactions of the Royal Society of London, Series B Biological Sciences 2005; 360: 359–372.
37. Farjon A. A Handbook of the World's Conifers. Brill, Leiden, Netherlands and Boston, U.S.A; 2010.
38. Collen B, Purvis A, Gittleman J. Biological correlates of description date in carnivores and primates. Global Ecology and Biogeography 2004; 13: 459–467.
39. Joppa LN, Roberts DL, Myers N, Pimm SL. Biodiversity hotspots house most undiscovered plant species. Proceedings of the National Academy of Sciences USA 2011b; 108: 13171–13176.
40. Pielou EC. Mathematical ecology, 2nd edition. Wiley and Sons, New York, USA; 1977.
41. Butchart SHM, Akçakaya HR, Chanson J, Baillie JEM, Collen B, Quader S, et al. Improvements to the Red List Index. PLoS ONE 2007; 2: e140. PMID: 17206275
42. IUCN. IUCN Red List Categories, version 3.1. Prepared by the IUCN Species Survival Commission. IUCN, Gland, Switzerland, UK; 2001.
43. IUCN. Guidelines for using the IUCN Red List Categories and Criteria, version 11. Prepared by the Standards and Petitions Sub-committee; 2014b. Available: www.iucnredlist.org/documents/RedListGuidelines.pdf
44. Willis F, Moat J, Paton A. Defining a role for herbarium data in Red List assessments: a case study of Plectranthus from eastern and southern tropical Africa. Biodiversity and Conservation 2003; 12: 1537–1552.
45. Bachman S, Moat J, Hill AW, de la Torre J, Scott B. Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. ZooKeys 2011; 150: 117–126. doi: 10.3897/zookeys.150.2109 PMID: 22207809
46. Wildlife Conservation Society (WCS), Centre for International Earth Science Information Network (CIESIN), Columbia University. Last of the Wild Project, Version 2: Global Human Footprint Dataset (Geographic). NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY, USA; 2005. http://dx.doi.org/10.7927/H4M61H5F.
47. IUCN, UNEP-WCMC. World Database on Protected Areas. Cambridge, UK; 2010. Now available at: www.protectedplanet.net
48. Center for International Earth Science Information Network (CIESIN), Columbia University, UN Food and Agriculture Programme (FAO), Centro Internacional de Agricultura Tropical (CIAT). Gridded Population of the World, Version 3: Population Count Grid. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY, USA, 2005. http://dx.doi.org/10.7927.H4639MPP.
49. Rivers MC, Bachman SP, Meagher TR, Nic Lughadha EM, Brummitt NA. Subpopulations, locations and fragmentation: applying IUCN Red List criteria to herbarium specimen data. Biodiversity and Conservation 2010; 19(7): 2071–2085.
50. Rivers MC, Taylor L, Brummitt NA, Meagher TR, Roberts DL, Nic Lughadha EM. How many herbarium specimens are needed to detect threatened species? Biological Conservation 2011; 144: 2541–2547.
51. Faber-Langendoen D, Nichols J, Master L, Snow K, Tomaino A, Bittman R, et al. NatureServe Conservation Status Assessments: Methodology for Assigning Ranks. NatureServe, Arlington, VA, USA; 2012.
52. Hoffmann M, Hilton-Taylor C, Angulo A, Böhm M, Brooks TM, Butchart SHM, et al. The impact and shortfall of conservation on the status of the world's vertebrates. Science 2010; 330: 1503–1509. doi: 10.1126/science.1194442 PMID: 20978281
53. Bland LM, Collen B, Orme CDL, Bielby J. Predicting the conservation status of data-deficient species. Conservation Biology 2014; doi: 10.111/cobi.12372
54. Mittermeier RA, Gil PR, Mittermeier CG. Megadiversity: earth's biologically wealthiest nations. CEMEX, Mexico; 1997.
55. Stevens GC. The latitudinal gradient in geographical range: how so many species coexist in the tropics. The American Naturalist 1989; 133(2): 240–256.
56. Pimm SL, Jenkins CN, Abell R, Brooks TM, Gittleman JL, Joppa JL, et al. The biodiversity of species and their rates of extinction, distribution and protection. Science 2014; 344(6187): 1246752. doi: 10.1126/science.1246752 PMID: 24876501
57. de Queiroz LP. The Brazilian caatinga: phytogeographical patterns inferred from distribution data of the Leguminosae. In: Pennington R.T., Ratter J.A., Lewis G.P. (Eds.), Neotropical Savannas and

Seasonally Dry Forests: Plant Diversity, Biogeography and Conservation. CRC Press, Boca Raton, Florida, USA, 2006; pp. 121–157.

58. Cardoso D, de Queiroz LP. Diversidade de Leguminosae nas caatingas de Tucano, Bahia: implicações para a fitogeografia do semi-árido do Nordeste do Brasil. Rodriguésia 2007; 58: 379–391.
59. Yesson C, Brewer PW, Sutton T, Caithness N, Pahwa JS, Burgess M, et al. How global is the Global Biodiversity Information Facility? PLoS One 2007; 2: e1124. PMID: 17987112
60. Villaseñor JL, Maeda P, Rosell JA, Ortiz E. Plant families as predictors of plant biodiversity in Mexico. Diversity and Distributions 2007; 13: 871–876.
61. Oliveira-Filho AT, Cardoso D, Schrire BD, Lewis GP, Pennington RT, Brummer TJ, et al. Stability structures tropical woody plant diversity more than seasonality: insights into the ecology of high legume-succulent-plant biodiversity. South African Journal of Botany 2013; 89: 42–57.
62. Newton AC. Implications of Goodhart's Law for monitoring global biodiversity loss. Conservation Letters 2011; 4(4): 264–268.
63. Brummitt NA. Patterns in the global distribution of flowering plant genera. In Friis I., Balslev H. (eds.) Plant Diversity and Complexity Patterns: local, regional and global dimensions. Biologiske Skrifter 2005; 55: 539–564.
64. Grenyer R, Orme CDL, Jackson SF, Thomas GH, Davies RG, Davies TJ, et al. Global distribution and conservation of rare and threatened vertebrates. Nature 2006; 444: 93–96. PMID: 17080090
65. Jenkins CN, Pimm SL, Joppa LN. Global patterns of terrestrial vertebrate diversity and conservation. Proceedings of the National Academy of Sciences 2012; 110(28): E2602–E2610.
66. Joppa LN, Visconti P, Jenkins CN, Pimm SL. Achieving the Convention on Biological Diversity's goals for plant conservation. Science 2013; 341(6510): 1100–1103.
67. Rodriguez JP, Rodriguez-Clark KM, Baillie JEM, Ash N, Benson J, Boucher T, et al. Establishing IUCN Red List criteria for threatened ecosystems. Conservation Biology 2011; 25(1) 21–29. doi: 10.1111/j.1523-1739.2010.01598.x PMID: 21054525
68. MEA. Ecosystems and human well-being: scenarios. Island Press, Washington D.C., USA; 2005.
69. Foden WB, Butchart SHM, Stuart SN, Vié JC, Akçakaya HR, Angulo A, et al. Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. PLoS ONE 2013; 8(6): e65427. doi: 10.1371/journal.pone.0065427 PMID: 23950785
70. Carwardine J, Klein CJ, Wilson KA, Pressey RL, Possingham HP. Hitting the target and missing the point: target-based conservation planning in context. Conservation Letters 2011; 2(1): 4–11.
71. Martin LJ, Blossey B, Ellis E. Mapping where ecologists work: biases in the global distribution of terrestrial ecological observations. Frontiers in Ecology and the Environment 2012; 10:195–201.
72. Pereira HM, Belnap J, Brummitt N, Collen B, Ding H, Gonzalez-Espinosa M, et al. Global biodiversity monitoring. Frontiers in Ecology and the Environment 2010b; 8:459–460.
73. Schmeller DS, Julliard R, Bellingham P, Böhm M, Brummitt NA, Chiarucci A, et al. Developing a global terrestrial species monitoring program. Journal of Nature Conservation 2015; 25: 51–57.
74. Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, et al. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science 2013; 342: 850–853. doi: 10.1126/science.1244693 PMID: 24233722
75. Schmeller DS, Henry PY, Julliard R, Gruber B, Clobert J, Dziock F, et al. Advantages of volunteer-based biodiversity monitoring in Europe. Conservation Biology 2009; 23:307–316. doi: 10.1111/j.1523-1739.2008.01125.x PMID: 19183201

Figure S1 Diversity Simulation part 1 – Families

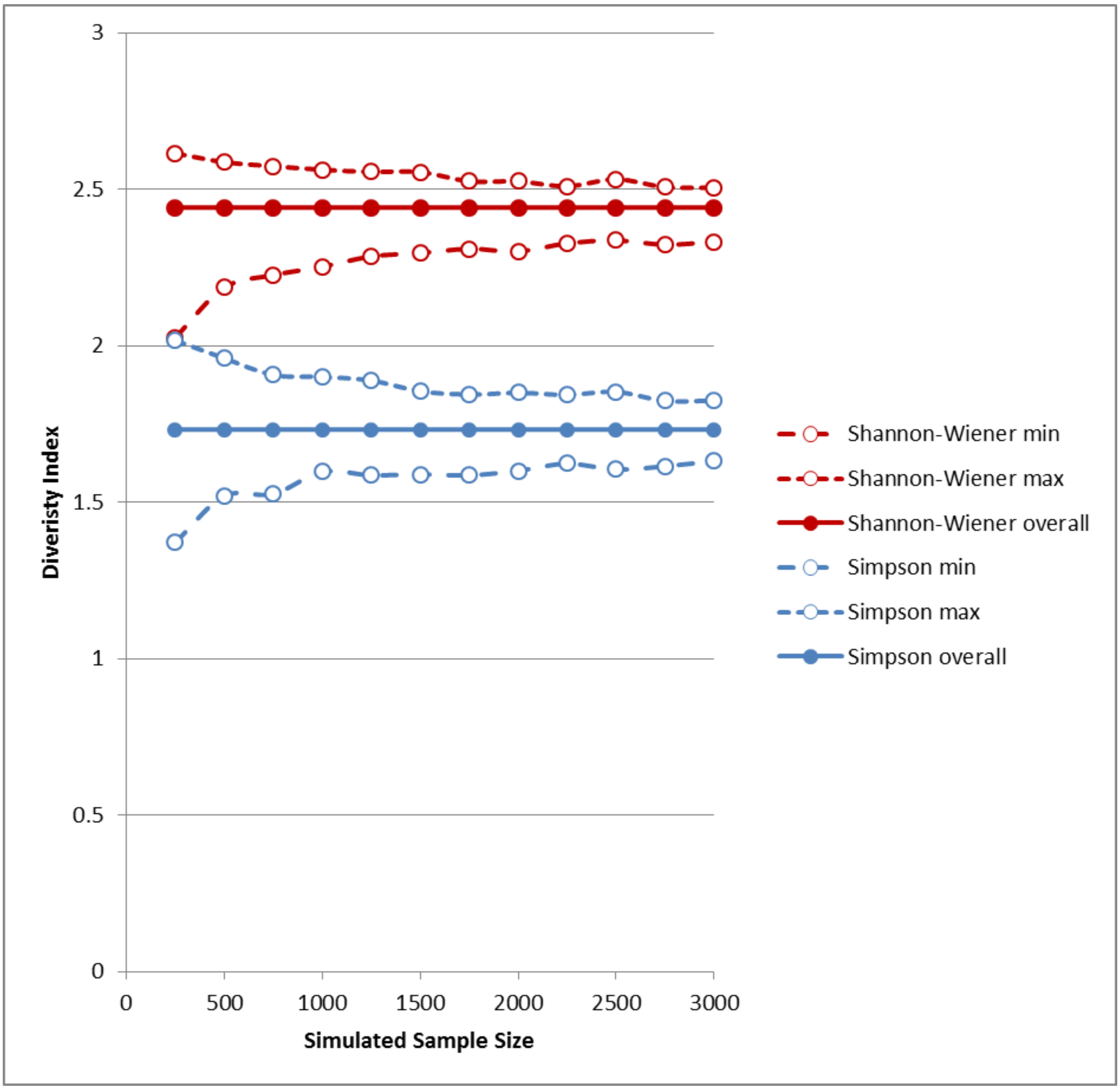
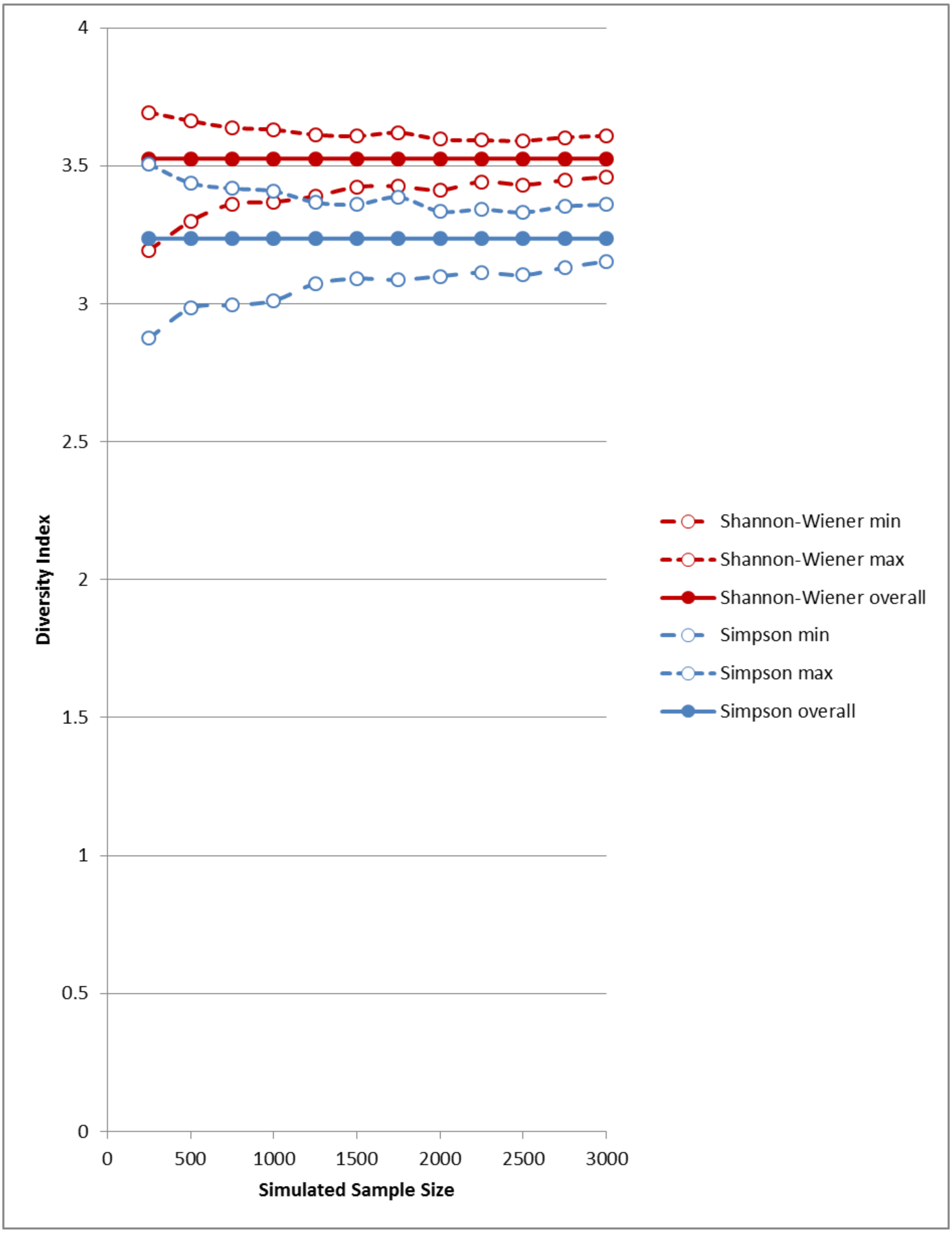
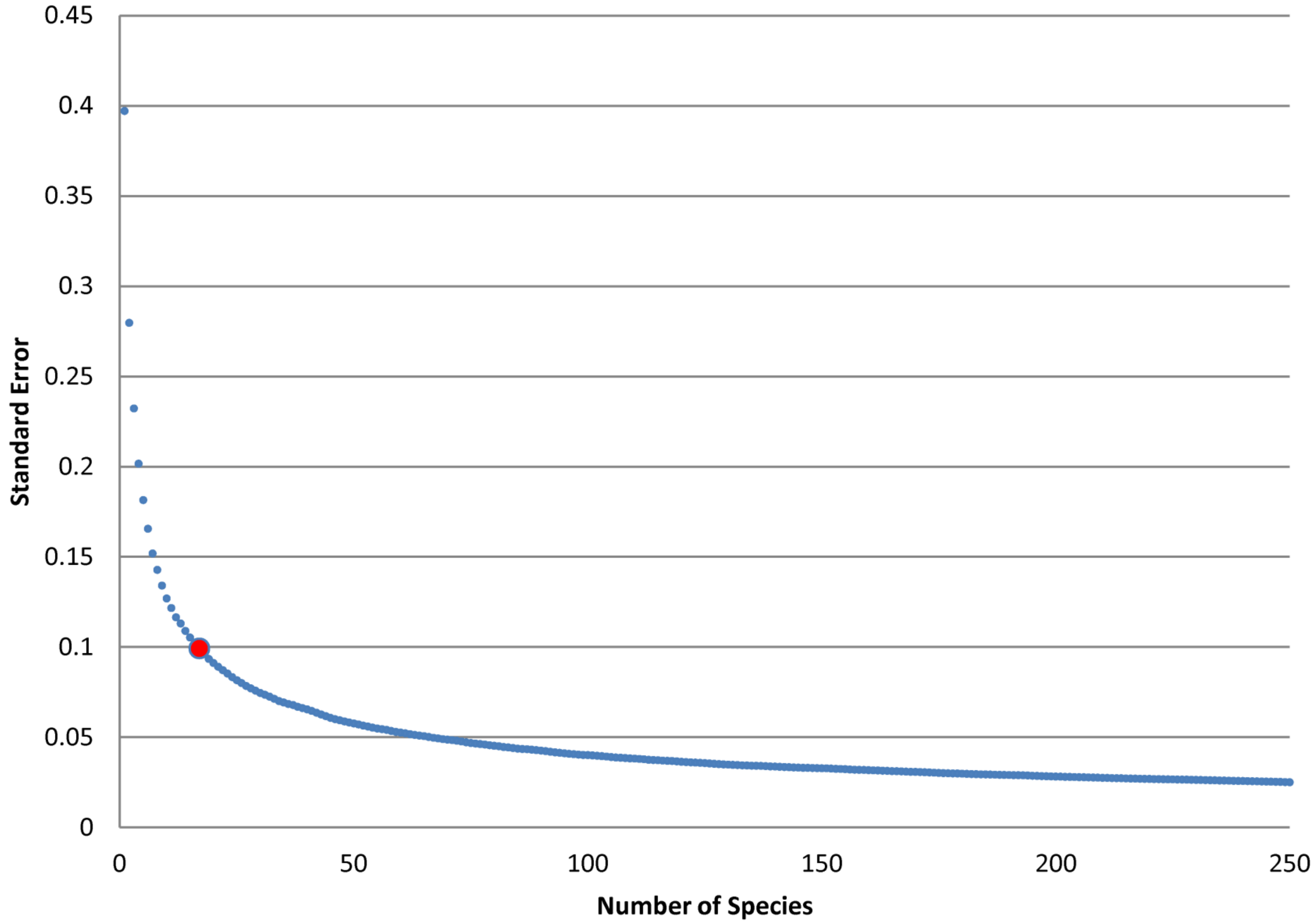


Figure S2 Diversity Simulation part 1 – Geographic Regions





Supplementary Figure S3 Plot of standard error against number of species sampled for 5,000 random simulations. The threshold value used for showing countries on the maps in Figure 4 (17 species) is highlighted in red.

Paper 2. GSPC Target 2

Towards a conservation assessment for all plants: a response to Target 2 of the Global Strategy for Plant Conservation

Status:

Published 21st December 2017

Citation:

Bachman, S. P., Nic Lughadha, E. M. and Rivers, M. C. (2018), *Quantifying progress toward a conservation assessment for all plants*. **Conservation Biology**, 32: 516-524. doi:10.1111/cobi.13071

https://onlinelibrary.wiley.com/doi/full/10.1111/cobi.13071

Authorship statement:

Authors: **Bachman, S.P.**, Rivers, M.C., Nic Lughadha, E.M.

SB is first author. SB, MR & ENL conceived and designed the experiments, SB & MR performed the experiments, analysed the data and SB, MR and ENL wrote the paper.

Conservation Biology

Conservation Practice and Policy

Quantifying progress toward a conservation assessment for all plants

Steven P. Bachman [1,2]* Eimear M. Nic Lughadha [1] and Malin C. Rivers [3]

[1]Royal Botanic Gardens, Kew, Richmond, Surrey TW9 3AE, U.K.
[2]School of Geography, University of Nottingham, Nottingham NG7 2RD, U.K.
[3]Botanic Gardens Conservation International, Richmond, Surrey TW9 3BW, U.K.

Abstract: *The Global Strategy for Plant Conservation (GSPC) set an ambitious target to achieve a conservation assessment for all known plant species by 2020. We consolidated digitally available plant conservation assessments and reconciled their scientific names and assessment status to predefined standards to provide a quantitative measure of progress toward this target. The 241,919 plant conservation assessments generated represent 111,824 accepted land plant species (vascular plants and bryophytes, not algae). At least 73,081 and up to 90,321 species have been assessed at the global scale, representing 21–26% of known plant species. Of these plant species, at least 27,148 and up to 32,542 are threatened. Eighty plant families, including some of the largest, such as Asteraceae, Orchidaceae, and Rubiaceae, are underassessed and should be the focus of assessment effort if the GSPC target is to be met by 2020. Our data set is accessible online (ThreatSearch) and is a baseline that can be used to directly support other GSPC targets and plant conservation action. Although around one-quarter of a million plant assessments have been compiled, the majority of plants are still unassessed. The challenge now is to build on this progress and redouble efforts to document conservation status of unassessed plants to better inform conservation decisions and conserve the most threatened species.*

Keywords: Convention on Biological Diversity, conservation planning, red lists, extinction risk, Global Strategy for Plant Conservation, threatened species, ThreatSearch

Cuantificación del Progreso Hacia la Evaluación de la Conservación para Todas las Plantas Bachman et al.

Resumen: *La Estrategia Global para la Conservación de Plantas (GSPC, en inglés) estableció el objetivo ambicioso de lograr una evaluación de la conservación para todas las plantas conocidas para el año 2020. Consolidamos evaluaciones sobre la conservación de plantas disponibles digitalmente y reconciliamos sus nombres científicos y estados de evaluación con los estándares predefinidos para proporcionar una medida cuantitativa del progreso hacia este objetivo. Las 241,919 evaluaciones generadas sobre la conservación de las plantas representan a 111,824 especies aceptadas de plantas terrestres (plantas vasculares y briofitas, algas no). Al menos 73,081 y hasta 90,321 especies han sido evaluadas a escala global, representando 21 – 26% de las especies de plantas conocidas. De estas especies de plantas, al menos 27,148 y hasta 32,542 están amenazadas. Ochenta familias de plantas, incluidas algunas de las más grandes como Asteraceae, Orchidaceae, y Rubiaceae están sub-evaluadas y deberían ser el foco del esfuerzo de evaluación si se quiere alcanzar el objetivo de la GSPC para el año 2020. Nuestro conjunto de datos está disponible en línea (ThreatSearch) y es una línea de base que puede usarse para apoyar directamente a otros objetivos de la GSPC y de las acciones de la conservación de plantas. Aunque se han recopilado alrededor de un cuarto de millón de evaluaciones sobre plantas, la mayoría de las plantas permanecen sin ser evaluadas. El reto ahora es construir sobre este progreso e intensificar los esfuerzos para documentar los estados de conservación de las plantas sin evaluación para informar de mejor manera las decisiones de conservación y conservar a la mayoría de las especies amenazadas.*

*email s.bachman@kew.org
Article impact statement: *Conservation assessments have been compiled for a quarter of all plants to meet the 2020 Global Strategy for Plant Conservation Target 2.*
Paper submitted June 21, 2017; revised manuscript accepted November 25, 2017.

DOI: 10.1111/cobi.13071

Palabras Clave: Convención sobre la Diversidad Biológica, especies amenazadas, Estrategia Global para la Conservación de Plantas, listas rojas, planeación de la conservación, riesgo de extinción, ThreatSearch

摘要: *全球植物保护战略 (GSPC) 设立了一个雄心勃勃的目标, 要在2020年前对所有已知植物物种进行保护评估。我们整合了数字化的植物保护评估, 并按照预设标准整理了它们的学名和评估状况, 从而为这一目标的进展提供了量化标准。所产生的241,919个植物保护评估代表了111,824种公认的陆生植物 (维管植物和苔藓, 不包括藻类) 。73,081—90,321个物种有全球水平的评估, 它们代表着21-26%的已知植物物种。在这些植物中, 27,148–32,542个物种是受威胁物种。80个科的植物, 包括一些如菊科、兰科和茜草科等最大的科, 受到的保护评估仍不足;如果要达到GSPC定下的2020年目标, 这些科应该作为未来评估工作的重点。我们的数据集可以在线获取 (ThreatSearch) , 并可以用作直接支持其它GSPC目标和植物保护行动的基准。尽管一百万份植物评估已经编制了约四分之一, 但大部分的植物仍没有得到评估。当前的挑战是, 在目前进展的基础上加倍努力记录未评估植物的保护状况, 从而更好地为保护决策和保护最濒危的物种提供支持。* ***翻译: 胡怡思; 审校: 胡义波***

关 键 词:《生物多样性公约》, 全球植物保护战略, 灭绝风险, 受威胁物种, ThreatSearch, 保护计划, 红色名录

Introduction

Despite the fundamental importance of plants to life on Earth (Díaz et al. 2006; Isbell et al. 2011), plants are increasingly subjected to the threats of habitat loss and land-use change (Newbold et al. 2016), invasive species (Vilà et al. 2011), overharvest (Brummitt et al. 2015), and stress associated with climate change (Urban 2015). The pressure that humans exert on natural resources such as plants is at an unprecedented level and may push the planet beyond safe limits (Steffen et al. 2015).

Attempts to address the issue of ongoing biodiversity loss have been made through international treaties such as the Convention on Biological Diversity (CBD). Parties to the CBD, most of the world's countries, committed to reducing biodiversity loss by 2020 (UNEP & CBD 2010*a*), but recent progress reports and projections suggest the trend of continued loss is likely to persist (Tittensor et al. 2014; Visconti et al. 2016). Plants are included in global biodiversity targets and are the focus of a more specific strategy: the Global Strategy for Plant Conservation (GSPC) (Wyse Jackson & Kennedy 2009). Adopted by the Conference of the Parties (CoP) to the CBD in 2002 (UNEP & CBD 2002), the first iteration of the GSPC aimed to guide plant conservation through 16 outcome-oriented targets to be delivered by 2010. The strategy galvanized plant conservation activity in botanical gardens and herbaria (Williams et al. 2012), and in 2010 the first target a "working list of known plant species" was achieved with the publication of the plant list (The Plant List [http://www.theplantlist.org]). The second target of the strategy, a "preliminary assessment of the conservation status of all known plant species" had not been achieved by 2010 (McNeely 2011). Failure to meet Target 2 means other dependent targets such as Target 7 ("threatened species conserved in situ") and Target 8 ("threatened species in ex situ collections") were missed, and the lack of a quantitative response made it difficult to determine exactly how much progress had been made toward each of these targets and what the remaining gaps in coverage were (McNeely 2011).

An updated version of the GSPC was adopted by the CBD CoP (CBD 2010). The new targets, to be met by 2020, include a revised version of Target 2: "assessment of the conservation status of all known plant species, as far as possible, to guide conservation action" (UNEP & CBD 2010*b*). Targets 7 and 8 were also updated and modified; however, they are still heavily dependent on delivery of Target 2 because they require a list of threatened species so that levels of in or ex situ conservation can be reported (UNEP & CBD 2010*b*).

The updated strategy includes a technical rationale and milestones to track progress. The milestones for Target 2 include a working list of conservation assessments; an interim list of threatened species; expansion of national- and regional-scale assessments to assist the global assessment; and calls for an assessment of threat status through a "globally representative sample" of plant species. The International Union for the Conservation of Nature (IUCN) Sampled Red List Index for Plants shows that about 1 in 5 plants are at risk of extinction, which directly addresses the milestone of assessing global threat status (Brummitt et al. 2015), and some progress has been made with subglobal assessments (Zamin et al. 2010), but an update is needed because many new subglobal assessments have been completed since 2010. Conservation assessments at subglobal scales can make an important contribution to the global target because when species are endemic to the region to which the assessment applies, they are equivalent to global assessments. Fifty-seven percent of all trees are single-country endemic species (Beech et al. 2017), and as many as 60% of plant species are estimated to be endemic to a single region (R. Govaerts & N. Black, personal communication), more specifically a single level-3 unit of the Taxonomic Database Working Group geopolitical system (Brummitt et al. 2001). The 60% figure reflects high endemism in a small number of megadiverse regions; endemism in most regions is much lower. Furthermore, even if a species is not endemic to a country or region, a subglobal assessment may still be important to that country or region because it can guide conservation action, the ultimate goal of the GSPC. However, a comprehensive, quantitative response has been lacking for a working list of conservation assessments and an interim list of threatened species.

Compilation of conservation assessments of plants has been attempted; one study reports nearly 60,000 unique plant assessments (Sharrock et al. 2014). The plant names from this preliminary compilation were not matched to a taxonomic name checklist. The resulting list of assessments is therefore less useful for plant conservation because assessments linked to synonyms or erroneous names may trigger inappropriate conservation responses. Therefore, an update is needed that includes the reconciliation of names against an appropriate taxonomic plant names checklist to ensure a consistent output that supports the goals of GSPC Target 2. An update is also needed to incorporate conservation assessments at global and subglobal scales published subsequent to this initial compilation (Bachman et al. 2011; Léon-Yánez et al. 2011; Martinelli & Moraes 2013; Raimondo et al. 2013).

We sought to compile a comprehensive baseline response to GSPC Target 2 by reviewing and consolidating the existing digitally available knowledge base of plant conservation assessment data. We aimed to produce a working list of assessments for use as an online resource. A list of assessed and threatened species could facilitate responses to other GSPC targets such as Targets 7 and 8 relating to threatened species conserved in and ex situ. Finally, we identified gaps in the taxonomic coverage of conservation assessments for plants and considered the importance of these results in the context of the GSPC and plant conservation.

Methods

Data Compilation and Interpretation

Our definition of plants included land plants, that is, all vascular plants (Angiosperms, Gymnosperms, Pteridophytes, Lycopods) and Bryophytes, but not Algae. Plant conservation assessments were assembled from a variety of sources including national red-data books, the global IUCN Red List, taxonomic treatments, and online databases. Assessments were made at different geographic and taxonomic scales and with different assessment systems and were published between 1978 and 2016. Although we included some data sets published in 2016, others were not available at the time of compilation; therefore, coverage of assessment data for 2016 is not comprehensive. Data sets were downloaded or obtained with permission (full list of sources in Supporting Information). All data sets were simplified to a standard structure (Supporting Information) before being merged and analyzed in Microsoft Access.

To compare assessments conducted under different systems, we summarized over 115 conservation-assessment designations into 5 broad threat categories: extinct, threatened, potentially threatened, not threatened, or data deficient (UNEP 2003; Callmander et al. 2010). Each conservation-assessment designation was mapped to 1 category (e.g., from the NatureServe ranking system G2 Imperiled mapped to threatened and G5 Secure mapped to not threatened). The majority of assessments followed IUCN categories and criteria version 3.1 (IUCN 2012) or previous versions, for example, 2.3 or pre-1991 (IUCN 1994), and were therefore straightforward to map to the 5 broad threat categories. We mapped other assessment ratings following existing standards, for example NatureServe rankings have been mapped to IUCN categories (Master et al. 2012), which could then be mapped to the broad threat categories. A smaller number of assessments were more generic and did not use a particular standard. For these we reviewed the assessment and manually assigned 1 of the 5 threat categories. A full list of assignments is in Supporting Information. We categorized the geographic scope of the assessment as global, unknown, or not global based on contextual information from the data source where provided.

Reconciling Plant Assessments to a Name Checklist

We matched the plant names from the conservation assessments to names on The Plant List 1.1 (The Plant List 2013). The Plant List (TPL) is a working list of all known plant species and includes over 1 million scientific names for land plants, with each name assigned a status of either accepted, synonym, or unresolved based on the taxonomic data sources used by TPL. We used TPL as our taxonomic checklist because of its broad coverage across taxonomic groups, accessibility, integration with name-matching tools, and use in reporting on Target 1 of the GSPC. The list follows the circumscriptions and nomenclature of the Angiosperm Phylogeny Group III (2009) classification, except for its use of alternative family names Compositae and Leguminosae, which we refer to as Asteraceae and Fabaceae, respectively. We attempted to match as many plant names as possible from the conservation assessment data set to names on TPL. We checked for an exact match to TPL based on the plant name used in the conservation assessment, including taxonomic authors where available. For names without a unique match (names from our assessment list matched >1 name in TPL or names did not exactly match any name in TPL), we used Plantminer web service (Carvalho et al. 2010) in a fuzzy matching approach. Plantminer applies name-matching rules that allow for problems commonly found with plant-name data such as incorrect spelling and misapplied gender (e.g., *album* rather than *alba* or *albus*). A threshold can be set that controls how conservative the name matching should be, where 1.0 is an exact match and 0.7 allows imperfect matches. We tested the matching threshold on a sample of names and determined an optimal value (0.925), which we used to check the remaining ambiguous or unmatched names. This method is fully explained in Supporting Information.

Accepted-Species List

To generate a list of accepted plant species, we took the list of assessments with plant names that matched names in TPL and filtered out all taxa below species level (infraspecific) because GSPC Target 2 explicitly refers to species. We then removed those assessments with names TPL recognizes as a "synonym" or "unresolved," which left assessments with "accepted" names. We eliminated duplicate names on the list.

Threat Status and Assessment Scale

A complicating aspect of the assessment data is that a species could be assessed multiple times with different threat ratings or at different geographic scales. Therefore, to investigate differences in threat status and geographic scale of species assessed, we used the species list as described above, prior to removal of duplicate names. For all assessments of accepted species, we generated totals for the number of different species in each threat category. We refined these groupings by splitting species by the geographic scale at which the assessment was made to ensure that a species was counted only once per threat category, even though it may have been assessed at different geographic scales. To achieve this, we built a list for each threat category by starting with all species assigned to that category and assessed on a global scale and then adding species assigned to that category, assessed at an unknown scale, and not already included. Finally, we added species assigned to that category, assessed at not global scale, and not already included. Duplicate species with the same threat rating and same geographic scale were removed. However, a species could be listed more than once in different threat categories, meaning the sum of species across different threat categories will therefore be slightly higher than the total generated for the previously described accepted species list.

Gaps in Taxonomic Coverage

We investigated the distribution of conservation-assessment effort across taxonomic groups. We used number of species in a family, from the TPL website, for each family with ≥100 species and calculated the proportion of species in each family that had been assessed and determined whether families were overassessed, underassessed, or within the expected variation around the mean (Supporting Information). Because of high rates of synonymy in Pteridophytes and uncertainty over family delimitations (Christenhusz & Chase 2014), we restricted this analysis to seed plants (i.e., Angiosperms and Gymnosperms).

ThreatSearch

All assessments included in the analysis are in ThreatSearch (http://www.bgci.org/threat_search.php), a searchable online resource. The assessment data is accessed by entering search criteria such as scientific name and the scope of the assessment, such as global or nonglobal, can be used as a filter. Search results show name, published assessment status, interpreted status, year, scope, and source of assessment.

Results

Overview, Name Matching, and Species List

We found 241,919 unique conservation assessments of 111,824 unique accepted plant species (Fig. 1). On a global scale, at least 73,081 and up to 90,321 species have been assessed, of which 27,148–32,542 have been assessed at least once with a threatened category.

Name Matching and Accepted-Species List

A total of 219,775 assessments were matched to names on TPL (Fig. 1). After filtering out taxa below species level, synonyms, and unresolved names and eliminating duplicate species names, the total accepted species names was 111,824 (Fig. 1). Thus, 111,824 species (accepted name in TPL) had at least 1 assessment of their conservation status published.

Conservation-Assessment Categories and Globally Threatened Species

We found 121,087 accepted species × threat category combinations. The not threatened category contained the largest number of species (51,775), followed by threatened (37,543) and possibly threatened (17,850) (Fig. 2).

Most assessments were carried out at global or unknown scales (Fig. 2). In the strictest sense, the working list of conservation assessments should be at the global scale; thus, 73,081 accepted plant species (21%) have been assessed. However, if one assumes 60% of the 28,733 species assessed at an unknown scale are equivalent to global assessments because 60% of species are endemic to a single region, a further 17,240 species can be added to the global total to make a plausible maximum of 90,321 (26%).

At least 27,148 species were assessed as threatened. Again, if one assumes 60% of the 8,990 species with assessments rated as threatened at unknown scale are equivalent to global, a further 5,394 species can be

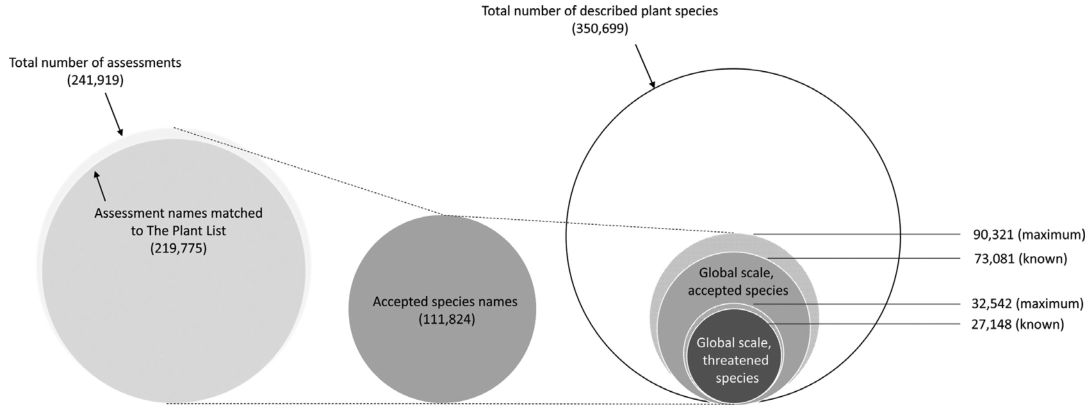


Figure 1. Illustration of the refinement of data from raw counts of plant assessments to only those with species names matched to The Plant List (circles on the left) and then further refinement to accepted species according to The Plant List (middle circle). Circles on the right show estimates for the total number of accepted species assessed at the global scale. The maximum estimate is based on the assumption that 60% of assessments of unknown scale are equivalent to global assessments. The smallest circles on the right show number of global assessments of threatened species; maximum estimate is again based on the 60% assumption. Global assessments are shown in the context of all described plants according to The Plant List (largest circle on the right).

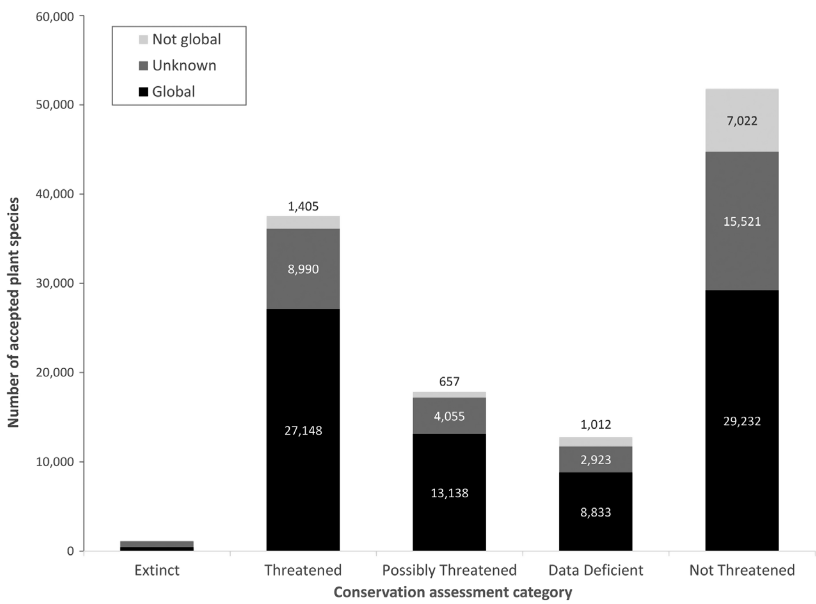


Figure 2. Breakdown of accepted plant species by threat category (extinct, threatened, possibly threatened, data deficient, and not threatened) and counts of species further split by geographical scale of assessment (global, unknown, not global). Data for the extinct category were too few to be clearly labeled on the graph (global, 460 species; unknown, 666; not global, 25).

added for a plausible maximum total of 32,542 threatened species assessed. Our quantitative response to GSPC Target 2 is therefore that 21–26% of accepted plant species have been assessed and 8–9% of all plant species are threatened. However, the percentage of assessed species that are threatened is much higher at 30–44%.

Taxonomic Gaps

When considering only families with ≥100 species, the average proportion of species assessed per family was 0.38 (Fig. 3). There was wide variation in the proportion of species assessed; some families such as Zamiaceae and Magnoliaceae were almost completely assessed, whereas some families such as Orchidaceae, Asteraceae, and Rubiaceae were underassessed relative to the average. Eighty families (45%) were underassessed, 55 (31%) were overassessed, and 43 (24%) were within the expected variation around the mean.

Discussion

Our findings suggest a considerable effort has been made to document the conservation status of plant species, but major gaps remain. We believe our quantitative approach

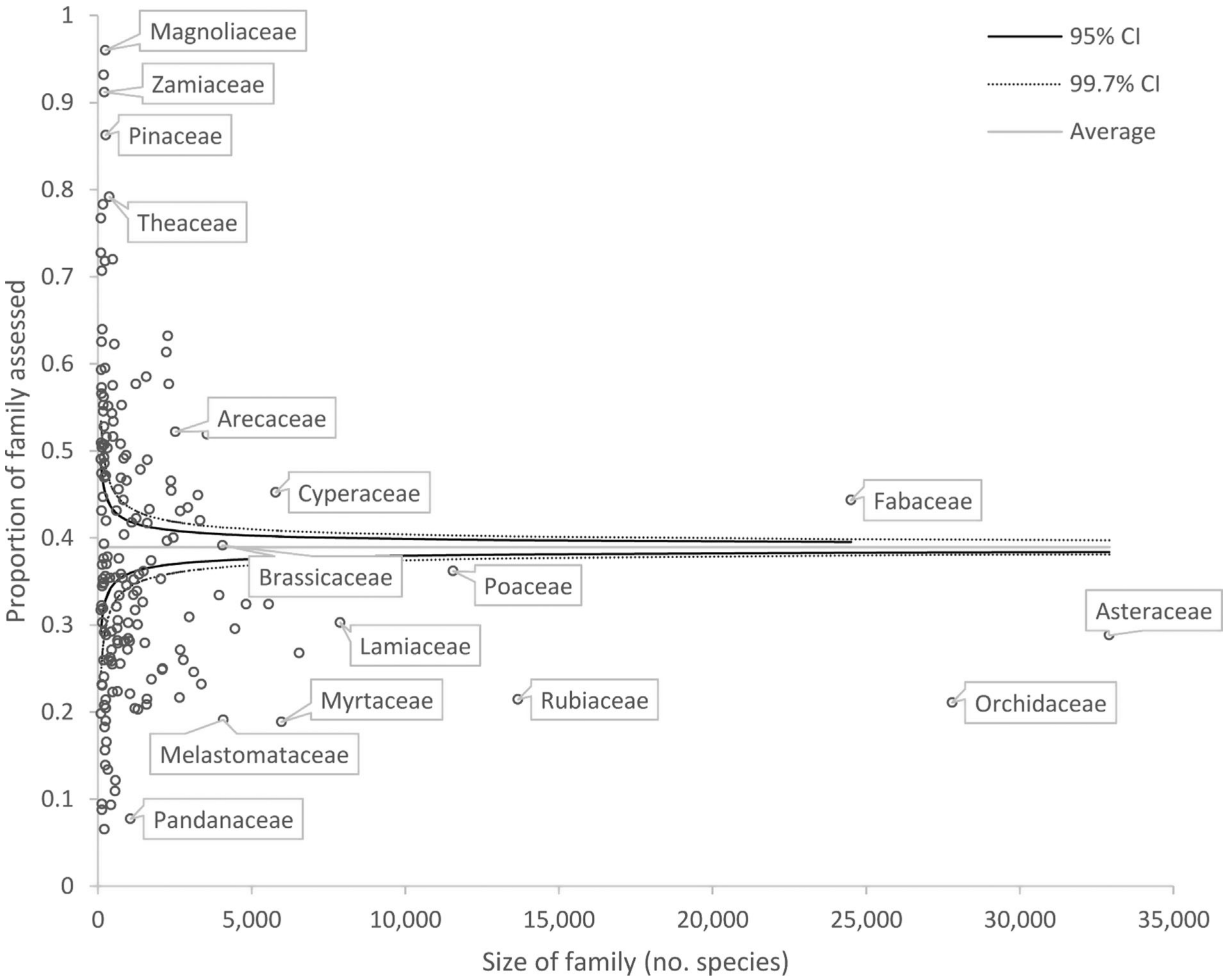


Figure 3. The relationship between the number of species per plant family and the proportion of species assessed per plant family (solid grey line, mean proportion assessed [0.39]; solid black line, 95% CI based on 1.96 SE; dotted line, 97.5% CI based on 3 SE). Family numbers are based on The Plant List (2013). Only families with ≥100 species are included. Labels highlight examples of families that are overassessed (Magnoliaceae, Zamiaceae) or underassessed (Pandanaceae, Melastomataceae). Of the larger plant families, the Asteraceae, Orchidaceae, and Rubiaceae are all underassessed and Fabaceae are overassessed. Brassicaceae are within the bounds of expected variation.

produced the most comprehensive review of progress toward GSPC Target 2 to date. The resulting collation of assessment data is in ThreatSearch. Our method can be repeated as further conservation assessments are published and as plant-name lists are further developed, enabling progress against GSPC Target 2 to be tracked as the 2020 deadline approaches.

Importance of Assessments at Different Scales

Our database included conservation assessments at different geographic scales, including global, regional, and local scale assessments of varying relevance for a quantitative response to a global-level target. With better data on geographic scale of assessments, these estimates could be further refined, and we encourage those producing assessments to clearly define their scale and taxonomic concepts. The GSPC Target 2 rationale explicitly notes that national- and regional-scale assessments are important to assist in delivery of the global target, and we acknowledge this by including all assessments, independent of scale, in ThreatSearch. As has been argued elsewhere (Schatz 2009), it is important that national- and regional-scale assessments be monitored.

Gaps in Data Coverage

We believe our compilation represents the most comprehensive list of plant assessments to date, but recognize there is a wealth of additional assessment data that could be gathered to extend coverage. Journals that publish taxonomic treatments of plants often include a section on the conservation status for each species; these could be incorporated in our combined list, potentially amounting to thousands of assessments per year. A recent step toward automating that process is a template developed by the *Biodiversity Data Journal* that can be used to publish assessments in a format that facilitates submission to the IUCN (Cardoso et al. 2016). We recommend that journals publishing taxonomic treatments of new plants encourage authors to include an assessment of conservation status of the new taxa. *Kew Bulletin*, for example, has encouraged inclusion of conservation assessments with taxonomic revisions since the early 2000s (D. Simpson, personal communication 2016).

Our search is likely to have covered the majority of published data sets for plant conservation assessments, especially those that were digitally accessible, although an unquantified amount of assessments appear in books in libraries (e.g., red-data books). The National Red List project (http://www.nationalredlist.org/) is a focal point for assessments in such books and was a major contributor to our compiled list, but it has limited resources to make red-data books digitally accessible. An alternative approach is to prioritize these books for inclusion in existing digitization projects such as the Biodiversity Heritage Library (http://www.biodiversitylibrary.org/) and then link assessments to ThreatSearch.

Name Matching and Summarizing Threat Categories

A consequence of our automated procedure is a failure to link some names used in assessments to the TPL names checklist. Even though we used fuzzy matching to account for inexact matches, our approach was conservative to minimize the number of false matches because linking a conservation assessment to the wrong name would be unhelpful. Insufficient resources were available to carry out a manual inspection of nonmatching assessments, which would resolve this issue, but this should be attempted prior to the next update of the list. When publishing conservation assessments, carefully documenting plant names based on standard nomenclature would facilitate the matching process and ultimately lead to a clearer picture of which species should be conserved.

Name matching revealed many assessments bearing names that TPL treats as synonyms. In some cases, the species concept of the assessment bearing the synonym may be the same as the species concept for the accepted name, indicating the assessment could have been appropriately incorporated into our data set. The species-by-species research required to evaluate circumscriptions of even a sample of these names was beyond the scope of our project. Similarly, name matching revealed that some assessments were treated as unresolved names in TPL. The latest version of TPL (1.1) dates from September 2013 and therefore does not include additions and changes to plant names published since then. With creation of world Flora databases (http://www.worldfloraonline.org and http://plantsoftheworldonline.org), many more names will be updated, ultimately leading to the inclusion of more assessments linked to names with their status resolved. The impact of using alternative taxonomic name backbones (e.g., Catalogue of Life) should also be explored.

As our assessments were summarized to broad threat categories, we lost detail. Our decision to map assessments to these categories allowed us to summarize overall threat status, but terms such as possibly threatened may be too vague. To minimize risk of misinterpretation of this summary of threat status, we provide a link via ThreatSearch to the original assessment so that it can be viewed in its uninterpreted state. ThreatSearch also includes assessments linked to infraspecific names we excluded so as to report at the species level.

With these caveats in mind, we believe our estimates of the number of plant species assessed are likely to be conservative. It therefore follows we underestimated the number of species assessed as threatened species. More plant assessments exist and efforts should be made to consolidate these for future analysis. It is also likely that further effort reviewing unmatched or partially matched names will yield more data. Although maximizing coverage is important to the overall GSPC Target 2, we sought to develop a workable method that produces a baseline response that can be readily updated.

Beyond the 2017 Response to GSPC Target 2

To achieve a conservation assessment for all plants by 2020 still poses a major challenge, but our compilation shows considerable progress has been made. This response to GSPC Target 2 provides a baseline for further monitoring and highlights remaining gaps in coverage. To ensure the best chance of achieving Target 2, these gaps require immediate attention. Our approach is rigorous and repeatable and will support monitoring of the target and, through the dissemination of assessments through the *ThreatSearch* website (https://www.bgci.org/threat_search.php), can be used immediately to facilitate direct conservation action. We hope our results and outputs will draw attention to this important target and be used to inform a strategy for achieving an assessment of all plants by 2020.

Another benefit of our compilation is that it can be used as a prioritization tool. Work continues to broaden the taxonomic scope of the global red list through initiatives such as the Biodiversity Barometer (Stuart et al. 2010) and the Global Tree Assessment (Newton et al. 2015; Rivers 2017), and our list can be used to prioritize potentially threatened taxa for full IUCN Red List assessment and publication on the IUCN Red List. To achieve this one can query ThreatSearch for species assessed as threatened or possibly threatened and make these priorities for full global IUCN assessments. This supports broader targets for biodiversity conservation, including Aichi Biodiversity Target 12 and other GSPC targets (e.g., Targets 7 and 8). This first analysis of all known conservation assessments of plants shows the majority of plant species still lack a conservation assessment, which ultimately hampers application of limited conservation resources to achieve maximum conservation impact.

Acknowledgments

We thank S. Edwards and B. Allkin for carrying out the TPL name matching, R. O'Sullivan for digitizing Plant Red Data Books, M. Böhm for supplying plant assessments from the National Red List data set, and R. Field, S. Hargreaves, and J. Moat for comments that improved an earlier version manuscript.

Supporting Information

Conservation-assessment data sources (Appendix S1), structure and definition of fields used in the analysis (Appendix S2), assessment designation (Appendix S3), Plantminer threshold testing (Appendix S4), and the proportion of species assessed per family (Appendix S5) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

Bachman SP, Moat J, Hill A, De La Torre J, Scott B. 2011. Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. ZooKeys **150:**117–126.

Beech E, Rivers M, Oldfield S, Smith PP. 2017. GlobalTreeSearch: The first complete global database of tree species and country distributions. Journal of Sustainable Forestry **36:**454–489.

Brummitt NA, et al. 2015. Green plants in the red: a baseline global assessment for the IUCN sampled red list index for plants. PLOS ONE **10** (e0135152) https://doi.org/10.1371/journal.pone.0135152.

Brummitt RK, Pando F, Hollis S. 2001. Plant taxonomic database standards no. 2. World geographical scheme for recording plant distributions. Page plant taxonomic database standards. 2nd edition. Hunt Institute for Botanical Documentation, Carnegie Mellon University, Pittsburgh. Available from http://web.archive.org/web/20160125135239/http://www.nhm.ac.uk/hosted_sites/tdwg/TDWG_geo2.pdf (accessed June 2016).

Callmander MW, Schatz GE, Porter P Lowry. 2010. Red List assessment and the Global Strategy for Plant Conservation: taxonomists must act now. Taxon **54:**1047–1050.

Cardoso P, Stoev P, Georgiev T, Senderov V, Penev L. 2016. Species conservation profiles compliant with the IUCN Red List of Threatened Species. Biodiversity Data Journal **4** (e10356) https://doi.org/10.3897/BDJ.4.e10356.

Carvalho GH, Cianciaruso MV, Batalha MA. 2010. Plantminer: A web tool for checking and gathering plant species taxonomic information. Environmental Modelling & Software **25:**815–816.

CBD (Convention on Biological Diversity). 2010. X/17. Consolidated update of the Global Strategy for Plant Conservation 2011–2020. CBD, Montreal. Available from http://www.cbd.int/decision/cop/?id=12283 (accessed September 2016).

Christenhusz MJM, Chase MW. 2014. Trends and concepts in fern classification. Annals of Botany **113:**571–594.

Díaz S, et al. 2006. Biodiversity loss threatens human well-being. PLOS Biology **4** (e277) https://doi.org/10.1371/journal.pbio.0040277.

Isbell F, et al. 2011. High plant diversity is needed to maintain ecosystem services. Nature **477:**199–202.

IUCN (International Union for Conservation of Nature). 1994. The IUCN red list categories and criteria. IUCN, Gland, Switzerland.

IUCN (International Union for the Conservation of Nature). 2012. IUCN red list categories and criteria. Version 3.1. 2nd edition. IUCN, Gland, Switzerland.

Léon-Yánez S, Valencia R, Pitman N, Endara L, Ulloa C, Navarrete H. 2011. Libro rojo de las plantas endémicas del Ecuador. 2nd edition. Pontificia Universidad Católica del Ecuador, Quito.

Martinelli G, Moraes MA. 2013. Livro vermelho da flora do Brasil. Centro de Conservação da Flora, Rio de Janeiro.

Master LL, Faber-Langendoen D, Bittman R, Hammerson GA, Heidel B, Ramsay L, Snow K, Teucher A, Tomaino A. 2012. NatureServe conservation status assessments: factors for evaluating species and ecosystem risk. NatureServe, Arlington, Virginia. Available from http://www.natureserve.org/sites/default/files/publications/files/natureserveconservationstatusfactors_apr12_1.pdf (accessed January 2017).

McNeely JA. 2011. What more can plant scientists do to help save the green stuff? Botanical Journal of the Linnean Society **166:**233–239.

Newbold T, et al. 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science **353:**288–291.

Newton A, Oldfield S, Rivers M, Mark J, Schatz G, Garavito NT, Cantarello E, Golicher D, Cayuela L, Miles L. 2015. Towards a global tree assessment. Oryx **49:**410–415.

Raimondo DC, von Staden L, Donaldson JS. 2013. Lessons from the conservation assessment of the south african megaflora 1. Annals of the Missouri Botanical Garden **99:**221–230.

Rivers MC. 2017. The global tree assessment - red listing the world's trees. BGJournal **14:**16–19.

Schatz GE. 2009. Plants on the IUCN Red List: setting priorities to inform conservation. Trends in Plant Science **14:**638–642.

Sharrock S, Oldfield S, Wilson O. 2014. Plant conservation report 2014: a review of progress in implementation of the global strategy for plant conservation 2011–2020. Secretariat of the Convention on Biological Diversity, Montreal.

Steffen W, Broadgate W, Deutsch L, Gaffney O, Ludwig C. 2015. The trajectory of the Anthropocene: the great acceleration. The Anthropocene Review **2:**81–98.

Stuart SN, Wilson EO, McNeely JA, Mittermeier RA, Rodríguez JP. 2010. Ecology. The barometer of life. Science **328:**177.

The Plant List. 2013. The plant list. Available from http://www.theplantlist.org/ (accessed November 2015).

Tittensor DP, et al. 2014. A mid-term analysis of progress toward international biodiversity targets. Science **346:**241–244.

UNEP (United Nations Environment Programme). 2003. Implementation of the global strategy for plant conservation. UNEP, Montreal.

UNEP (United Nations Environment Programme) and CBD (Convention on Biological Diversity). 2002. VI/9. UNEP and CBD, Montreal. Available from https://www.cbd.int/doc/decisions/COP-06-dec-en.pdf (accessed January 2017).

UNEP (United Nations Environment Programme) and CBD (Convention on Biological Diversity). 2010*a*. The strategic plan for biodiversity 2011–2020 and the Aichi Biodiversity Targets. UNEP and CBD, Montreal. Available from https://www.cbd.int/decision/cop/?id=12268 (accessed June 2016).

UNEP (United Nations Environment Programme) and CBD (Convention on Biological Diversity). 2010*b*. Global Strategy for Plant Conservation: Technical rationale, justification for updating and suggested milestones and indicators. UNEP and CBD, Montreal. Available from http://www.cbd.int/doc/meetings/cop/cop-10/official/cop-10-19-en.doc (accessed June 2016).

Urban MC. 2015. Accelerating extinction risk from climate change. Science **348:**571–573.

Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P. 2011. Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. Ecology Letters **14:**702–708.

Visconti P, et al. 2016. Projecting global biodiversity indicators under future development scenarios. Conservation Letters **9:**5–13.

Williams SJ, Jones JPG, Clubbe C, Sharrock S, Gibbons JM. 2012. Why are some biodiversity policies implemented and others ignored? Lessons from the uptake of the Global Strategy for Plant Conservation by botanic gardens. Biodiversity and Conservation **21:**175–187.

Wyse Jackson P, Kennedy K. 2009. The Global Strategy for Plant Conservation: a challenge and opportunity for the international community. Trends in Plant Science **14:**578–580.

Zamin TJ, Baillie JEM, Miller RM, Rodriguez JP, Ardid A, Collen B. 2010. National red listing beyond the 2010 target. Conservation Biology **24:**1012–1020.

Supporting information

Appendix S1. List of data sources for raw conservation assessment data. Data was downloaded where available or requested from source providers. In some cases, only part of the dataset was provided i.e. some datasets only included assessments where the plant growth form was a tree. In some cases, only 'threatened' assessments were provided – see notes for more details.

Dataset	Citation	Notes
Acer Red List	Gibbs D & Chen Y (2009) The Red List of Maples. Flora & Fauna International, Cambridge	
Andes Red List	Tejedor Garavito N et al. (2014) A Regional Red List of Montane Tree Species of the Tropical Andes. BGCI, Richmond.	
Betulaceae Red List	Shaw K, Stritch L, Rivers M, Roy S, Wilson B & Govaerts R (2014) The Red List of Betulaceae. BGCI, Richmond.	
Bolivian Red List	Ministerio de Medio Ambiente y Agua (2012) Libro Rojo de la Flora amenazada de Bolivia. Vol. I. Zona Andina. MMAyA, La Paz. Andina. La Paz. 600 p.	
Caucasus Red List	Eastwood A (2005) Globally threatened trees of the Caucasus. A report on the Caucasus regional tree Red Listing workshop held in Tbilisi, Georgia, 26–28 Sep 2005. Fauna & Flora International, Cambridge.	
Central Asia Red List	Eastwood A, Lazkov G & Newton A (2008) The Red List of Trees of Central Asia. Fauna & Flora International, Cambridge	
China Red List	Ministry of Environmental Protection and the Chinese Academy of Sciences (2014) Chinese Red List of biodiversity - the volume of higher plants.	
Chua et al. 2010	Chua LSL, Suhaida M, Hamidah M & Saw LG (2010) Malaysia Plant Red List Peninsular Malaysia Dipterocarpaceae, Research Pamphlet No. 129, FRIM.	Part. Last accessed 11/11/16
Colling 2005	Colling G (2005) Red List of the Vascular Plants of Luxembourg. Ferrantia 42.	
Cuba Red List	Lazcano Lara et al. (eds.) (2005) Memorias del Primer Taller para la Categorización de Árboles Cubanos. 11-13 mayo 2004. Jardín Botánico Nacional. Ciudad de La Habana, Cuba.	
Ecuador Red List	León-Yánez S, Valencia R, Pitman N, Endara L, Ulloa Ulloa C & Navarrete H (eds) (2012) Libro Rojo de las Plantas Endémicas del Ecuador, Segunda edición. Universidad Católica del Ecuador, Quito.	
Ethiopia & Eritrea Red List	Vivero JL, Kelbessa E & Demissew S (2005) The Red List of Endemic Trees and Shrubs of Ethiopia and Eritrea. Fauna & Flora International, Cambridge	

González-Torres et al. 2013	González-Torres LR, Palmarola A, Barrios D. & González-Oliva L (2013) Las 50 plantas más amenazadas de Cuba. Bissea 7(NE 1)	
Guatemala Red List	Vivero JL, Szejner M, Gordon J & Magin G (2006) The Red List of trees of Guatemala. Fauna & Flora International, Cambridge.	
IUCN Plants 1997	Walter KS & Gillett HJ (eds) (1998) 1997 IUCN Red List of Threatened Plants. IUCN, World Conservation Union, Cambridge.	
IUCN_2016_1	IUCN Red List of Threatened Species v. 2016.1 www.iucnredlist.org	
IUCN_RedList_2016_1_regional	IUCN Red List of Threatened Species v. 2016.1 www.iucnredlist.org - regional assessments	
Jordan Red List	Taifour H & El-Oqlah A (2014) Jordan Plant Red List. Royal Botanic Garden, Jordan.	
Kew_CAT	An unpublished bibliography of publications which include assessments, many being papers with a primarily taxonomic focus	
Korean Red List of Threatened Species CD	Sang-Bae, Kim (ed.) (2014) Korean Red List of Threatened Species. 2nd ed. N.p.: National Institute of Biological Resources, CD.	CR/EN trees only. Last accessed 31/10/14
Livro Vermelho da Flora do Brasil 2013	Martinelli G & Moraes MA (2013) Livro vermelho da flora do Brasil. CNCFlora, Rio de Janeiro. Tradução Flávia Anderson, Chris Hieatt. - 1. ed. - Rio de Janeiro: Andrea Jakobsson: Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, 2013.	Remainder. Last accessed 18/11/2016
Magnolia Red List	Cicuzza D, Newton AC & Oldfield S (2007) The Red List of Magnoliaceae. Fauna & Flora International, Cambridge	
MalaysiaFloraDatabase	Forest Research Institute Malaysia (2015) Malaysia Flora Database. Available at: http://www.chm.frim.gov.my/Bio-Diversity-Databases/Flora-Database.aspx	Endemic CR/EN trees only. Last accessed 20/01/15
Mesoamerica Red List	Gordon J (2005) Red Listing of Mesoamerican dry forest tree species. Fauna & Flora International, Cambridge.	
Mexico Red List	González-Espinosa M et al. (ed) (2011) A Red List of the Mexican Cloud Forest Trees. Fauna & Flora International, Cambridge	
Miller & Neale 2015	Miller & Neale (2015) Provisional IUCN Red List of Iraq's endemic plants. http://iraqdarwin.org/download/1043/	
Namibian Tree Red List	Loots S (2005) A Red Data Book of Namibian Plants. SABONET Report No. 38. Pretoria; Loots S (2010) Unpublished assessments of the Namibian Botanical Research Institute of Namibia.	CR/EN only
National Red List 0915	National Red List www.nationalredlist.org	Last accessed 09/2015

NatureServe	NatureServe http://www.natureserve.org/	Last accessed 2014
NOM_2010	SEMARNAT (2010) Norma Oficial Mexicana NOM-059-SEMARNAT-2010 http://www.profepa.gob.mx/innovaportal/file/435/1/NOM_059_SEMARNAT_2010.pdf	
Planear	PlanEAr, plantas endémicas de la Argentina. http://www.lista-planear.org/	Endemics only. Last accessed 06/2016
Quercus Red List	Oldfield S & Eastwood A (2007) The Red List of Oaks. Fauna & Flora International, Cambridge	
Rakotoarisoa et al. 2014	Rakotoarisoa SE, Klopper RR & Smith GF (2014) A preliminary assessment of the conservation status of the genus Aloe L. in Madagascar. Bradleya 32/2014: 81–91	
Rankou et al. 2015	Rankou H, Culham A, Sghir Taleb M, Ouhammou A, Martin G & Jury SL (2015) Conservation assessments and Red Listing of the endemic Moroccan flora (monocotyledons). Botanical Journal of the Linnean Society, 177(4), pp.504-575.	
Rhododendron Red List	Gibbs D, Chamberlain D & Argent G (2011) The Red List of Rhododendrons. Fauna & Flora International, Cambridge	
Romeiras et al. 2015	Romeiras et al (2016) IUCN Red List assessment of the Cape Verde endemic flora: towards a Global Strategy for Plant Conservation in Macaronesia. Botanical Journal of the Linnean Society.	
Sao Tomé tree list	Figueiredo E (2010) Unpublished assessments of trees of S.Tomé and Príncipe (draft). Centro de Ecologia Funcional, University of Coimbra. Portugal.	CR/EN only. Last accessed 29/10/14
South Africa Trees	SANBI (2014) Red List of South African Plants. Available at: http://redlist.sanbi.org/	Last accessed 06/11/2014
South African Plants SANBI	SANBI (2014) Plants of Southern Africa. Available at: http://posa.sanbi.org/searchspp.php	Last accessed 06/11/2014
Taxonomic treatment papers	Additional assessments listed in taxonomic treatment papers not previously included in KewCAT. Each assessment is individually referenced in ThreatSearch	
The Red List of Korean Endemic Vascular Plants (Leaflet)	Korea Plant Specialist Group (2014) The Red List of Korean Endemic Vascular Plants - Korea National Aboretum,	CR/EN trees only
Threatened Plants of the Philippines	Fernando ES et al. (2008) Threatened plants of the Philippines–a preliminary assessment. Philippine Plant Conservation Committee, Department of Environment and Natural Resources.	CR/EN only - left out Dryopteridaceae, Cyatheaceae
Trees of Uganda	Kalema J & Beentje H (2012) Conservation checklist of the trees of Uganda. Kew, Richmond, Surrey, UK: Kew Pub.	
Trinidad and Tobago Red List	Van den Eyden V, Oatham MP & Johnson W (2008) How free access internet resources	

	benefit biodiversity and conservation research: Trinidad and Tobago's endemic plants and their conservation status. Oryx 42(3): 400-407	
Vietnam Red Data Book Part II: Plants	Ban NT, Ly TD, Khoi NK (2007) Vietnam Red Data Book Part II. Plants. Ministry of Science and Technology/ Vietnamese Academy of Science and Technology, Hanoi.	CR/EN Dicots + Monocots only

Appendix S2. Data structure and definition of fields used in analysis.

Field heading	Definition
ID	Internal ID
SourceID	Source ID in original dataset or generated if no ID existed
Family	Taxonomic family as provided by original dataset
Genus	Taxonomic genus as provided by original dataset
Species	Taxonomic species as provided by original dataset
Author1	Taxonomic author as provided by original dataset
InfraSpecRank	Infra specific rank as provided by original dataset
InfraSpecName	Infra specific epithet as provided by original dataset
Author2	Infra specific author as provided by original dataset
AssessmentYear	Year in which assessment was made. If not listed, assumed to be the year of publication.
ConsAssCategory	Verbatim conservation status from source dataset
ConsAssCriteria	Verbatim conservation status from source dataset
BGCI_Scope	Scale of assessment – simplified to Global, not global, unknown
Threatened	Interpretation of 'ConsAssCategory' field according to a pre-defined list of options comprising of 'Threatened'; 'Possibly Threatened'; 'Not Threatened'; 'Data Deficient'; and 'Extinct'
Reference	Source of original assessment.
BGCI_URL	URL of source assessment
TaxonName	Created from taxonomic names fields
AcceptedNameID	ID from The Plant List
ReferenceID	ID for reference source
Comment	Notes

Appendix S3. Unique assessment designations mapped to one of the five summarised categories. The majority of assessments used the strict or modified IUCN categories (IUCN version 2.3 or 3.1), as well as the pre 1991 categories, which mapped well to the summarised categories: 'Extinct', 'Threatened', 'Potentially Threatened', 'Not Threatened', or 'Data Deficient'. We followed existing mapping approaches where they existed (Master et al. 2012), except for NatureServe rank G3 and T3 that more closely mapped to the 'Threatened' category. Otherwise we interpreted each rating on a case-by-case basis using information from the source publication or any other contextual information. The table shows translations for unique assessment designations with 10 or more assessments associated with them.

Raw assessment designations from different data sources	Summarised category	Count of assessments	Source for rating system
LC	Not Threatened	61850	IUCN (2.3 or 3.1)
VU	Threatened	23304	IUCN (2.3 or 3.1)
EN	Threatened	17939	IUCN (2.3 or 3.1)
R	Possibly Threatened	16327	IUCN pre-1991
DD	Data Deficient	14881	IUCN (2.3 or 3.1)
CR	Threatened	11117	IUCN (2.3 or 3.1)
NT	Possibly Threatened	11107	IUCN (2.3 or 3.1)
V	Threatened	8382	IUCN pre-1991
G5	Not Threatened	7489	NatureServe
Not Threatened	Not Threatened	7144	NZTCS, ILDIS
E	Threatened	6958	IUCN pre-1991
G4	Not Threatened	5680	NatureServe
I	Data Deficient	4185	IUCN pre-1991
Category interpreted from text.	Possibly Threatened	3305	Kew CAT
G3	Threatened	3165	NatureServe
T4	Not Threatened	2118	NatureServe
Insufficiently known	Data Deficient	1987	IUCN pre-1991
T5	Not Threatened	1872	NatureServe
G2	Threatened	1838	NatureServe
T3	Threatened	1576	NatureServe
G1	Threatened	1493	NatureServe

LR/lc	Not Threatened	1460	IUCN (2.3)
EX	Extinct	1280	IUCN (2.3 or 3.1)
LR/nt	Possibly Threatened	1097	IUCN (2.3)
RE	Extinct	1028	IUCN (2.3 or 3.1)
A	Threatened	1023	NOM
Naturally Uncommon	Possibly Threatened	950	NZTCS
T2	Threatened	934	NatureServe
5	Threatened	839	Planear
Rare	Possibly Threatened	635	IUCN pre-1991
T1	Threatened	615	NatureServe
Category interpreted from text.	Threatened	502	Kew CAT
C1	Threatened	471	Red List of vascular plants of the Czech Republic
Pr	Threatened	455	NOM
4	Possibly Threatened	423	Planear
EX/E	Threatened	400	IUCN pre-1991
3	Not Threatened	386	Planear
C2	Threatened	357	Red List of vascular plants of the Czech Republic
C3	Threatened	355	Red List of vascular plants of the Czech Republic
GU	Data Deficient	272	NatureServe
NA (No Amenazado)	Not Threatened	243	CUBA
A[2]	Threatened	240	Cuba RL
C4a	Possibly Threatened	233	Red List of vascular plants of the Czech Republic
LR/cd	Possibly Threatened	223	IUCN (2.3)
Nationally Critical	Threatened	222	NZTCS
Category interpreted from text.	Data Deficient	207	Kew CAT
CR(PE)	Threatened	193	IUCN (3.1)
P	Threatened	184	NOM
Vulnerable	Threatened	159	IUCN (pre 1991, 2.3 or 3.1)
GH	Threatened	157	NatureServe
Declining	Possibly Threatened	157	NZTCS

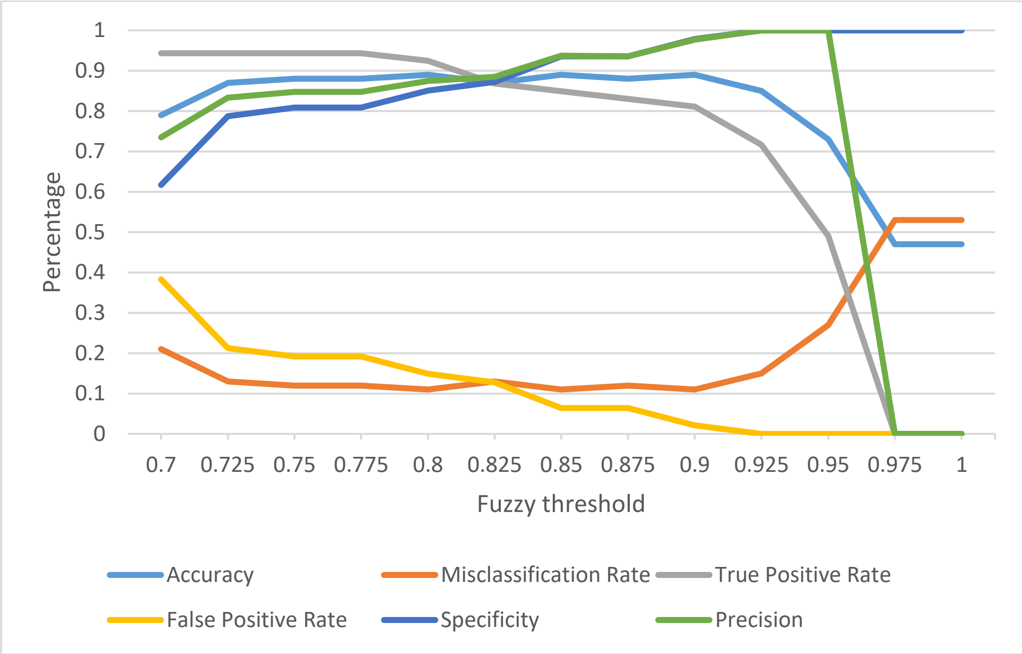
TU	Data Deficient	155	NatureServe
C4b	Data Deficient	147	Red List of vascular plants of the Czech Republic
CR/EN	Threatened	138	IUCN (2.3 or 3.1)
Endangered	Threatened	130	IUCN (pre 1991, 2.3 or 3.1)
A[1+2]	Threatened	123	Cuba RL
Category interpreted from text.	Not Threatened	119	Kew CAT
Nationally Vulnerable	Threatened	113	NZTCS
Data Deficient	Data Deficient	113	IUCN (2.3 or 3.1)
Extinct	Extinct	112	IUCN (pre 1991, 2.3 or 3.1)
[Threatened]	Threatened	111	Canada Red List; Chile Red list
Indeterminate	Possibly Threatened	98	IUCN pre-1991
A {2}	Threatened	93	Cuba RL
Nationally Endangered	Threatened	87	NZTCS
EW	Extinct	84	IUCN (pre 1991, 2.3 or 3.1)
A {2+4}	Threatened	79	Cuba RL
A1	Extinct	74	Red List of vascular plants of the Czech Republic
CA	Possibly Threatened	72	Cuba RL
Critically endangered	Threatened	70	IUCN (2.3 or 3.1)
A {1+2+4}	Threatened	68	Cuba RL
A[1+2+4]	Threatened	64	Cuba RL
2	Not Threatened	60	Planear
CR PE	Threatened	59	IUCN (3.1)
A2	Extinct	53	Red List of vascular plants of the Czech Republic
NT(VU)	Possibly Threatened	52	IUCN (2.3 or 3.1)
A[2+4]	Threatened	50	Cuba RL
A {1+2}	Threatened	50	Cuba RL
TH	Threatened	48	NatureServe
Very Rare	Possibly Threatened	43	Malta Red List
Category interpreted from text.	Extinct	40	Kew CAT
[Not threatened]	Not Threatened	40	Canada Red List

VU*	Threatened	38	IUCN (2.3 or 3.1)
1	Not Threatened	38	Planear
NT*	Possibly Threatened	34	IUCN (2.3 or 3.1)
NT[1+2]	Not Threatened	32	IUCN (2.3 or 3.1)
A {4}	Threatened	31	Cuba RL
RE/EN	Extinct	30	IUCN (2.3 or 3.1)
LRnt	Possibly Threatened	30	IUCN (2.3)
A3	Extinct	29	Red List of vascular plants of the Czech Republic
EN*	Threatened	25	IUCN (2.3 or 3.1)
Relict	Possibly Threatened	23	NZTCS
LRcd	Possibly Threatened	23	IUCN (2.3)
A[4]	Threatened	23	Cuba RL
Lower Risk: Least Concern	Not Threatened	22	IUCN (2.3)
Extinct	Threatened	22	IUCN (pre 1991, 2.3 or 3.1)
A[1]	Threatened	20	Cuba RL
NT[1]	Not Threatened	19	IUCN (2.3 or 3.1)
LR	Not Threatened	19	IUCN (2.3)
?N	Threatened	19	Red List of Bulgarian Vascular Plants
GX	Extinct	18	NatureServe
Rare	Not Threatened	17	SANBI
CR (PE)	Threatened	17	IUCN (3.1)
Extinct/Endangered	Threatened	16	IUCN pre-1991
NT {1+2}	Possibly Threatened	14	IUCN (2.3 or 3.1)
A[1+4]	Threatened	14	Cuba RL
EN/RE	Threatened	13	IUCN (2.3 or 3.1)
A {1+4}	Threatened	13	Cuba RL
Unknown.	Data Deficient	12	KewCAT
Recovering	Possibly Threatened	12	NZTCS
NE	Data Deficient	11	KewCAT
Endangered (EN)	Threatened	11	IUCN (2.3 or 3.1)

Declining	Not Threatened	11	SANBI
A[1+2+3+4]	Threatened	11	Cuba RL
A {1+2+3+4}	Threatened	11	Cuba RL
RE/VU	Extinct	10	IUCN (2.3 or 3.1)

Appendix S4.

The relationship between different threshold values used in Plantminer and plant name classification success.



Notes

We outline here the methodology used to determine the most appropriate value for fuzzy matching of names using Plantminer. Plantminer applies name matching rules that allow for problems commonly found with plant name data such as incorrect spelling, or misapplied gender e.g. *album* rather than *alba* or *albus*. Plantminer provides the user with a threshold setting to control how conservative the 'guessing' should be, where 1.0 is equivalent to an exact match and 0.7 is more forgiving and allows imperfect matches, but may result in an erroneous match.

To establish the appropriate threshold for fuzzy matching we sampled 100 random names from our list of names with conservation assessments that had not matched TPL after an initial check for exact matches. We checked to see whether it should match to a TPL name or not and then subjected all 100 names to the Plantminer web service (Carvalho et al. 2010) and recorded whether it found a match or not. The fuzzy parameter in Plantminer ranges from 0.7 – 1.0 and we tested the accuracy of the matching from 0.7 – 1.0 at intervals of 0.025. We built a confusion matrix and classified the results into: Correct match (True positive); Incorrect – should have matched (False negative); Correct not to match (True negative) and Matched to wrong name (False positive). We noted the Accuracy, Misclassification Rate, True Positive Rate, False Positive Rate, Specificity, Precision, and Prevalence and plotted the results as shown below. A fuzzy value of 0.825 showed good balance between over and under-predictions, but we considered it to be more important to avoid false positives so used the false positive rate to determine the optimal fuzzy value. At 0.925 Plantminer doesn't make any false positive matches (from our sample), but by relaxing the matching to 0.9 and lower, the false positive rate increases, hence we chose 0.925 as our optimal value to use for the remaining ambiguous or unmatched names.

Table S4
Analysis of taxonomic gaps in threat assessments. Each family with ≥100 species was classified according to whether it was over-assessed, under-assessed, or within the expected variation around the mean.
Link to Excel spreadsheet here

https://onlinelibrary.wiley.com/action/downloadSupplement?doi=10.1111%2Fcobi.13071&file=cobi13071-sup-0002-AppendixS5.docx

References

Carvalho, G.H., Cianciaruso, M.V. & Batalha, M.A. (2010). *Plantminer: A web tool for checking and gathering plant species taxonomic information*. *Environ. Model. Softw.*

Master, L.L., Faber-Langendoen, D., Bittman, R., Hammerson, G.A., Heidel, B., Ramsay, L., Snow, K., Teucher, A. & Tomaino, A. (2012). *NatureServe Conservation Status Assessments: Factors for Evaluating Species and Ecosystem Risk*. Arlington, Virginia.

Paper 3. Red List Challenges

Progress, challenges and opportunities for Red Listing

Status:

Accepted at *Biological Conservation* 3rd March 2019.

Authorship statement:

Authors: **Bachman, S.P.**, Field, R., Reader, T., Raimondo, D., Donaldson, J., Schatz, G., Nic Lughadha, E.M.

SB is lead author. SB, RF, TR and ENL conceived and designed the experiments, SB performed the experiments and analysed the data, SB, RF, TR, DR, JD, GS and ENL wrote the paper.

Progress, challenges and opportunities for Red Listing

Authors & Affiliations:

Steven P. Bachman[1,2]*, Richard Field[2], Tom Reader[2], Domitilla Raimondo[3], John Donaldson[3], George Schatz[4], Eimear Nic Lughadha[1]

[1]Royal Botanic Gardens, Kew, Richmond, Surrey, TW9 3AE, UK

[2]School of Geography, University of Nottingham, Nottingham, NG7 2RD, UK

[3]South African National Biodiversity Institute, Private Bag X101, Silverton, 0184, South Africa

[4]Missouri Botanical Garden, P.O. Box 299, St. Louis, Missouri 63166-0299, USA

*__Author for correspondence__.

Steven P. Bachman, Research Leader, Species Conservation, Conservation Science, Royal Botanic Gardens, Kew, Richmond, Surrey TW9 3AE, UK. Email: s.bachman@kew.org; Phone: (+44) 208 332 5272

There are no competing interests to declare

Keywords:

Vascular plants; IUCN Red List; Extinction Risk; Conservation

Progress, challenges and opportunities for Red Listing

Abstract

Despite its recognition as an important global resource for conservation, the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species only provides assessments of extinction risk for a small and biased subset of known biodiversity. A more complete Red List can better support species-level conservation by indicating how quickly we need to act on species deemed to be priorities for conservation action.

Vascular plants represent one of the Red List knowledge gaps, with only 7% of species currently on the Red List (including in the Data Deficient and Least Concern categories). Using vascular plants as a case study we highlight how recent developments, such as changes to rules, improvements to data management systems, better assessment tools and training, can support Red List assessment activity. We also identify ongoing challenges, such as the need to support regional and national assessment initiatives, the largely voluntary nature of the Red List community, as well as the need to meet core operating costs for the Red List. Finally, we highlight how new opportunities such as automation and batch uploading can fast-track assessments, and how better monitoring of assessment growth can help assess the impact of new developments. Most of our findings are also applicable to other species-rich groups that are under-represented on the Red List.

We examine trends in plant Red Listing and conclude that the rate of new assessments has not increased in line with what would be required to reach goals like the Barometer of Life. This may result partly from a lag between recent changes and their effects, but further progress can be made by realising the opportunities outlined here and by growing the Red List community and strengthening collaboration with IUCN.

1. Introduction

The (IUCN) Red List of Threatened Species™ (hereafter the Red List) is an important global resource for conservation (Rodrigues et al., 2006). Faced with limited resources and ongoing threats (Symes et al., 2018), conservationists must prioritise their actions. Species-level prioritisation can be driven by different factors such as rarity (Ricketts et al., 2005), phylogenetic diversity (Faith, 1992) or 'keystone' ecological roles (Marsh et al., 2007), but incorporating extinction risk, the likelihood of extinction under prevailing conditions (Mace et al., 2008), is crucial in order that priorities reflect the urgency with which we need to act. Currently, the Red List is the most recognised global system and documents extinction risk of more than 96,951 species (IUCN, 2018a). However, this represents a small and a biased subset of biodiversity (Stuart et al., 2010) and it is crucial to make the Red List more representative if it is going to guide species-level prioritization.

1.1 Gaps and bias in Red List coverage

A major shortcoming of the Red List is its biased taxonomic coverage across the species-level diversity currently known to science. Comprehensive Red List assessments have been achieved for birds, mammals and amphibians, though assessment gaps for reptiles and fish limit overall coverage for vertebrates to 68% of described species (Table 1). Invertebrates, plants and fungi, on the other hand, are largely under-assessed, with an average assessment of <3% of known species (IUCN, 2018a) meaning the majority of the world's species have not had their risk of extinction evaluated.

	Estimated Number of described species	Number of species evaluated	Species evaluated as % of species described	Number of species not assessed
INVERTEBRATES	1,305,250	21,886	2	1,283,364
PLANTS*	417,801	27,514	7	390,287
FUNGI & PROTISTS	52,280	81	<1	52,199
VERTEBRATES	69,537	47,470	68	22,067

Table 1.

Progress in assessing extinction risk of major groups of organisms using the IUCN Red List system (IUCN, 2018a).

*The IUCN estimate of the number of described species of plants (310,442) has been replaced here by a more recent estimate of 417,801 based on an estimated number of land plants (including vascular plants and bryophytes of 403,911) (Nic Lughadha et al., 2016), plus 6,637 species of green algae (Chlorophyta) and 7,253 red algae (Rhodophyta) (Guiry and Guiry, 2019).

The need for both taxonomic and temporal expansion (i.e. repeat assessments to detect trends) of the Red List has been recognised (IUCN Red List Committee, 2013; Rondinini et al., 2013; Stuart et al., 2010). For groups like plants, it is hard to overstate the magnitude of the current gap in assessment coverage on the Red List - there are 390,287 plant species still to be assessed (Table 1). Using estimates of global threat status of plants (Brummitt et al., 2015) we can infer that as many as 115,291 of the Not evaluated plant species are of elevated conservation concern (i.e. in the threatened categories Critically Endangered, Endangered, Vulnerable, or Near Threatened), which is more than the estimated number of described vertebrates (Figure 1) and more than four times the number of all plants currently assessed on the Red List. The true value could be even higher if Data Deficient species are considered likely threatened (Bland et al., 2015), and yet higher still if we consider the estimated 10-20% of currently undescribed species (Joppa et al., 2010).

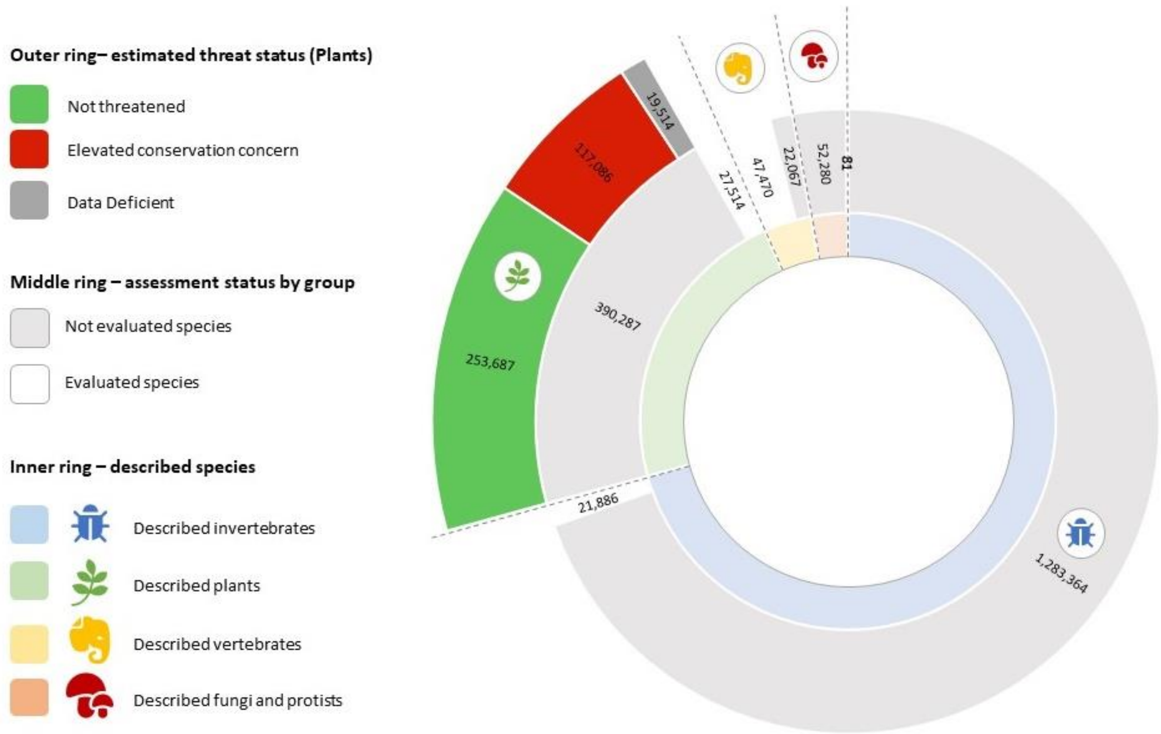


Figure 1.

Sunburst chart illustrating progress in assessing species for the IUCN Red List. The **inner ring** shows proportion of described species for major groups of organisms (Data from Table 1.; IUCN, 2018a). The **middle ring** shows the breakdown of evaluated (white segments) vs. not evaluated species (grey segments). The **outer ring** shows the breakdown of not evaluated plant species by estimated threat status of Least Concern, Threatened or Data Deficient. The number of plant species of elevated conservation concern (117,086) is more than the estimated number of described vertebrates (69,537). Data on number of described species and number of evaluated species from Table 1. Estimates of proportion Least Concern, Elevated conservation concern (including Critically Endangered, Endangered, Vulnerable and Near Threatened) and Data Deficient for plants is derived from the Sampled Red List Index for Plants (Brummitt et al., 2015).

Plant assessments have not accumulated on the Red List in a systematic way, they have been subject to several different types of bias. For example, assessors have prioritised species they expect to be threatened, leading to an average of ~48% of assessed species being considered threatened (Critically Endangered, Endangered or Vulnerable), when global estimates place the figure at 21% (Brummitt et al., 2015) (Figure 2).

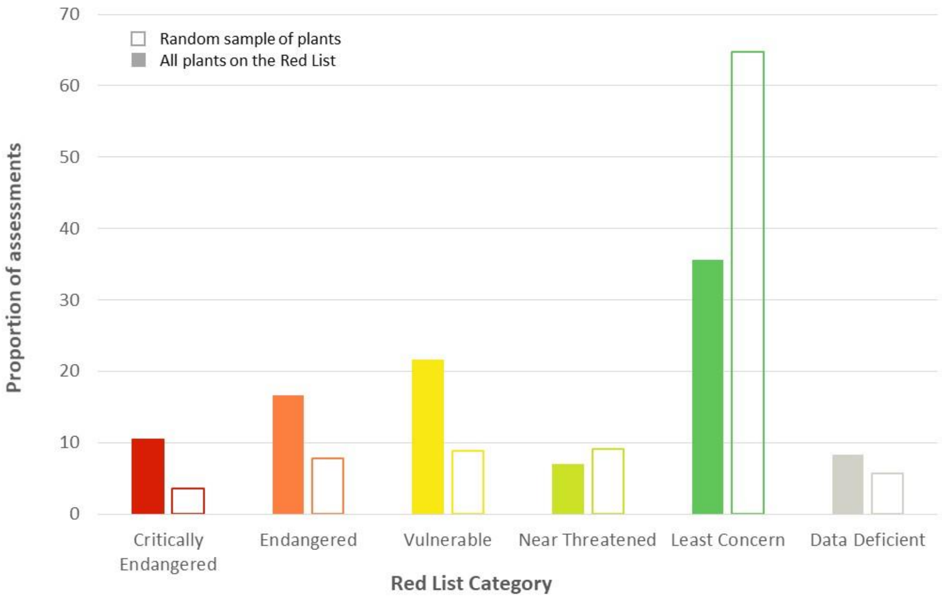


Figure 2

Comparison of number of plant species in Red List categories for all plants on the Red List (solid bars; source: IUCN Red List 2018-2) against a random sample (hollow bars; Brummitt et al., 2015)

Other forms of bias occur when certain groups of plants are targeted for assessment, usually driven by IUCN Specialist Groups (SGs) and Red List Authorities (RLAs). The remit of SGs is promoting and delivering conservation – including producing Red List assessments – for a focal group of species. There are 38 SGs or RLAs for plants, some with a taxonomic focus (e.g. Orchid SG), some with a geographic focus (e.g. Chinese Plant SG) and some with a thematic focus (e.g. Medicinal Plant SG) (Table S1). Three of the top ten most assessed plant families over the last ten years are under the remit of taxonomic SGs or RLAs: Cactaceae (Cactus & Succulent SG), Arecaceae (Palm SG) and Orchidaceae (Orchid SG) (Figure 3). Unsurprisingly, species within the remit of taxonomic SGs or RLAs are more likely to be assessed than expected by chance ($P<0.001$; Table S2). However, the large number of species in families such as Orchidaceae (29,700) means that there is still a considerable shortfall in species coverage (Table S3).

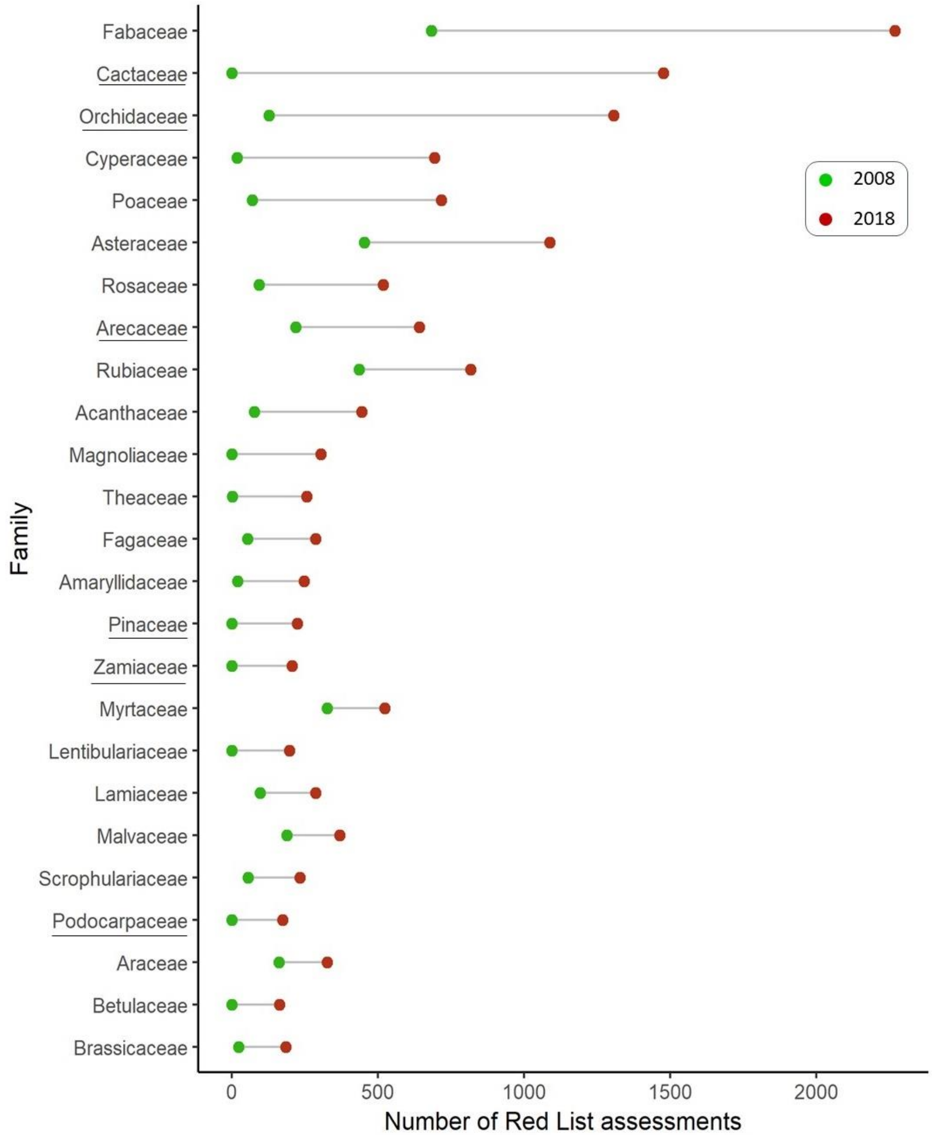


Figure 3

Comparison of number of species per family on the 2008 version of the Red List with the current 2018 Red List. The y axis is ranked by families with the highest increase in assessments over the last ten years (2008 – 2018). Families under the remit of taxonomic specialist groups are underlined. There is considerable variation in the number of species in each family - a full list of families along with proportion of species assessed is provided in Table S3. A plot of the proportion of species assessed per family is shown against size of the family (number of species) in figure S3.

The final major source of bias in plant Red List assessment is geographic. Coverage of plants on the Red List broadly reflects overall patterns of plant species richness and these are also reflected in the areas where the greatest number of not evaluated species occur (Figure 4).

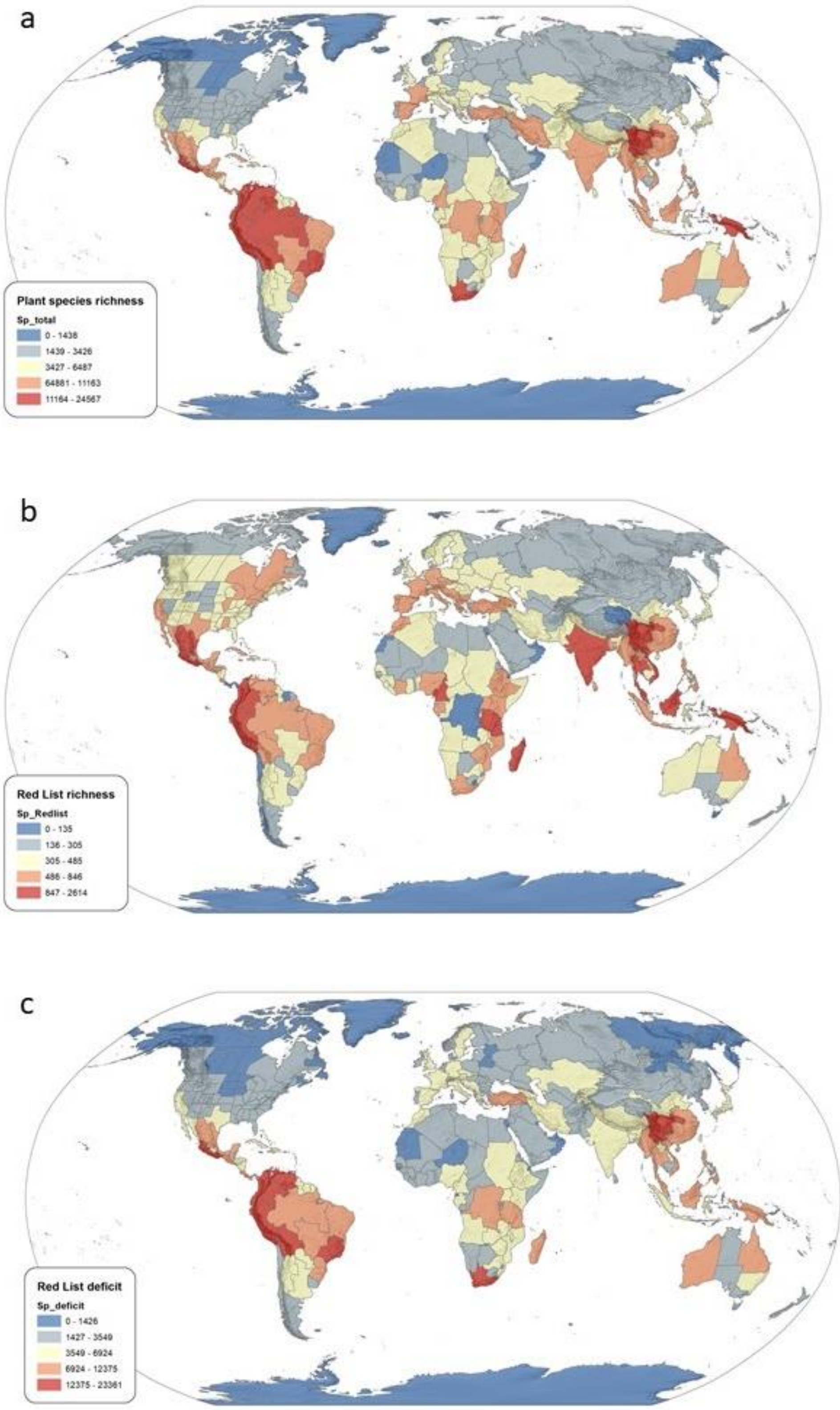


Figure 4.

(a) Plant species richness based on TDWG level 3 geographic regions (Source: Plants of the World Online), (b) Richness of plant species published on the IUCN Red List (IUCN, 2018a) and (c) Deficit of plant species Red List assessments (Red List richness subtracted from plant species richness).

1.2 Why the gaps matter

The lack of comprehensive Red List coverage for species-rich groups has precluded their inclusion in large-scale analyses of threat status and conservation actions across the globe (Boyd et al., 2008; Grenyer et al., 2006; Venter et al., 2014). It is important that non-vertebrate groups are added to such analyses because more comprehensive coverage of biodiversity can provide new insights for conservation science (Clausnitzer et al., 2009; Larsen et al., 2012; Rodrigues and Brooks, 2007). Hence, there has been a call to extend the taxonomic coverage of the Red List and develop a more complete 'Barometer of Life' by assessing 160,000 species by 2020 (Stuart et al., 2010). However, with 96,951 species assessments published since the criteria were updated in 2001 (IUCN, 2018a) , this will be challenging.

The gaps in coverage are also important because the Red List has become an increasingly vital tool to support conservation through its influence in the business sector (Bennun et al., 2018). For example, Performance Standard 6 of the International Finance Corporation (IFC) specifically incorporates species categorised as Critically Endangered (CR) or Endangered (EN) on the Red List in defining Critical Habitat. Development projects must offer protection for Critical Habitat or initiate remedial action (IFC, 2012). The Red List also influences the conservation funding sector, where a threatened species on the Red List can trigger funding through initiatives such as the Mohamed Bin Zayed Conservation Fund, IUCN's own SOS fund or the Critical Ecosystem Partnership Fund. A perhaps unintended consequence of this influence is that less value is attached to species considered threatened, but not currently documented on the Red List. Failure to document threatened species on the Red List restricts our ability to influence conservation via these mechanisms.

There is also value in assessing species for the Red List even if there is insufficient information to assign a category of extinction risk: Data Deficient (DD) species are recognised as targets for research (Bland et al., 2015; Howard and Bickford, 2014) and their publication on the Red List has been shown to produce a listing effect that increases associated research output (Jarić et al., 2017).

1.3 Growing the Red List – vascular plants as a case study

Using vascular plants as a case study, in the following sections we first review recent developments in Red List assessment rules, guidelines and information management, and the tools and techniques available to support assessments. We consider what impact these changes have had on the Red List and the extent to which they are likely to contribute to filling current gaps. Secondly, we consider ongoing challenges and issues influencing growth of the Red List. Finally, we explore opportunities for future work that may provide quick wins and can stimulate activity towards addressing knowledge gaps.

1.4 Overview of Red Listing process

To put the following sections into context, we outline a generalised Red List assessment workflow (Figure 5). There is no universally applied workflow, but Red Listing efforts often start with a species list, where species are either prioritised for assessment, or not (classified as Not Evaluated). This is followed by a pre-assessment stage where all available relevant data for each species are gathered. For plants this usually involves herbarium specimen data and observations ('occurrence data'), or information derived from floras or monographs. The assessment stage is where data are analysed to produce metrics that allow the Red List criteria to be applied. If insufficient data are available, a species can be classed Data Deficient (DD). If data are available to apply the criteria, and quantitative thresholds are met, a species can be assigned a threatened category: Critically Endangered (CR), Endangered (EN) or Vulnerable (VU). If thresholds are not met, but are close, a species may be Near

Threatened (NT). If a species is far from the thresholds, it can be categorized Least Concern (LC). The assessment can be a 'desktop' process (Brummitt et al., 2008), often carried out by an individual that can access specimen collection data and contact relevant experts, or it can be undertaken as part of a workshop where assessors, experts and facilitators process multiple assessments. Each assessment is then reviewed by an appropriate Red List Authority (RLA) or a delegated expert, or if no appropriate reviewer can be found, the Red List Unit. The review stage often results in feedback to the assessor(s) in an iterative process until there is agreement. Finally, assessments are submitted to the Red List Unit where they undergo consistency and quality checks before publication on the Red List.

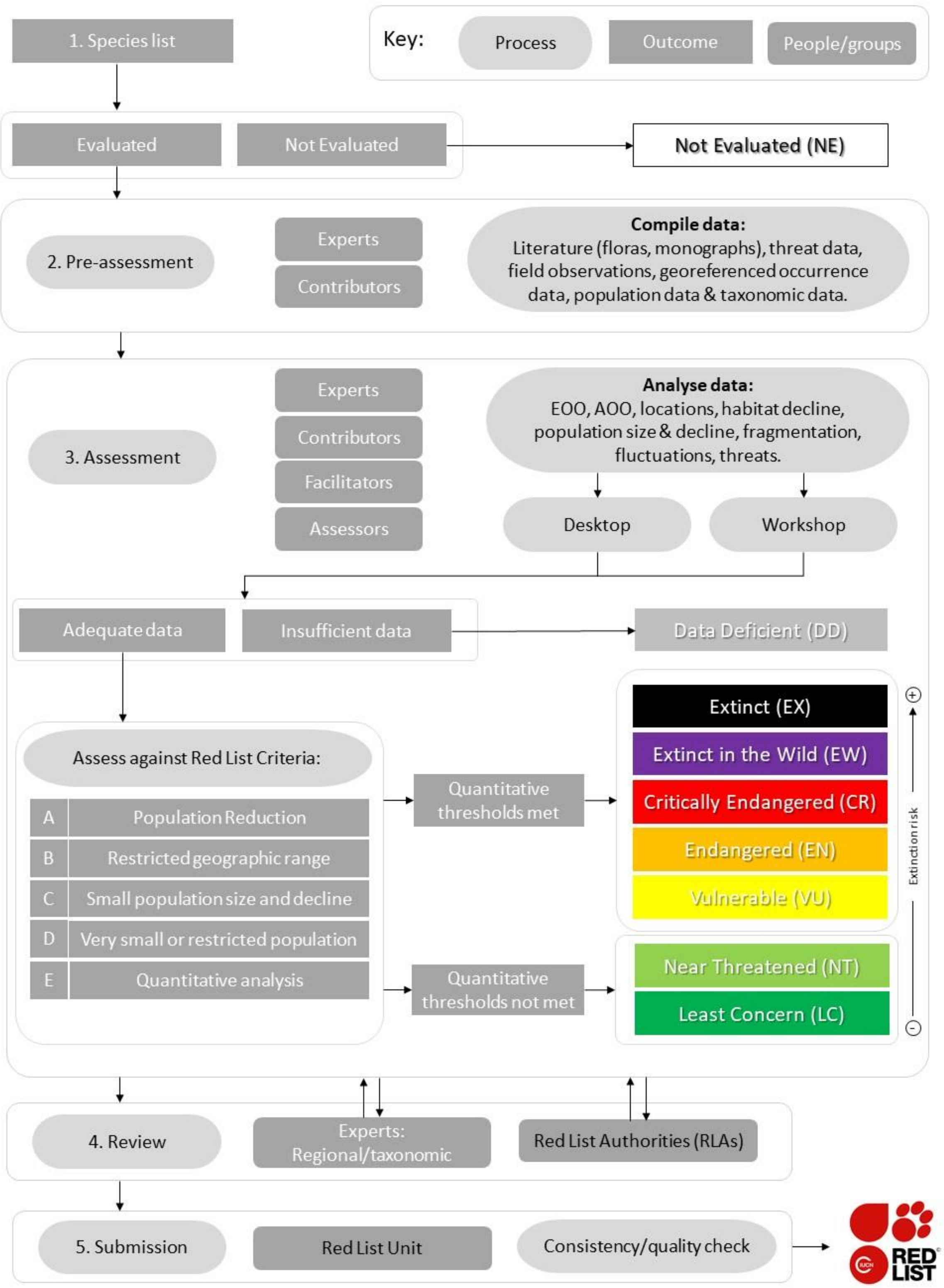


Figure 5. Generalised Red List assessment workflow from species list to publication on the Red List. Ovals represent processes, grey and coloured rectangles are outcomes and curved rectangles are people or groups. EOO = Extent of occurrence, AOO = Area of occupancy. Arrows indicate direction of flow through different stages, including feedback.

2. Recent developments

2.1 Automated criteria calculation and consistency checks

Red Listing is based on quantitative criteria that categorize species according to their likelihood of extinction under prevailing conditions (IUCN, 2001; Mace et al., 2008). The criteria are underpinned by metrics relating to extinction theory, such as small or declining populations (Mace and Lande, 1991) and the existence of immediate and plausible threats. Thresholds set for these metrics determine to which category a species should be assigned (IUCN, 2001). Manual interpretation of the criteria, even by trained assessors, can sometimes result in errors that need to be resolved, either through assessment review or by IUCN Red List Unit staff, the team ultimately responsible for publication and maintenance of the Red List. Manual corrections absorb time that could be spent processing error-free assessments. To assist assessors, an automated *criteria calculator* has been built into the online Red List data management system, the Species Information Service (SIS). This automatically assigns the most appropriate category based on the data that have been entered (IUCN, 2018b).

Efficiency is also lost towards the end of the assessment process when time is spent checking assessments for consistency, such as ensuring the minimum requirements have been met. To reduce this wasted effort, an *integrity checker* has been added to SIS that checks that the appropriate level of supporting data has been provided – see section 2.2. The use of the *criteria calculator* and *integrity checker* will help assessors generate 'technically' correct assessments. Enforcing use of these tools is unlikely to result in a significant increase in the generation of new assessments; rather it will help to free capacity of the Red List Unit to process more assessments, and act as a training aid that can reduce assessor bias (Hayward et al., 2015).

2.2 Reduced data requirements

The comprehensive, quantitative nature of each Red List assessment both makes the Red List a valuable tool and slows its expansion. Assessors have been deterred by having to document species in much more detail than may be necessary to assign Red List Categories with reasonable confidence, resulting in potential contributors to the Red List either failing to finalise assessments or resorting to publishing them elsewhere.

Lobbying by the IUCN Plant Conservation Committee (PCC) and the IUCN SSC South African Plant Specialist Group resulted in revised guidelines on supporting information requirements for Red List assessments (IUCN, 2016). The new guidelines identified that some data are not strictly required to support assessments and these fields were therefore downgraded to optional. Further, data requirements were differentiated according to the final category (e.g. minimal data are now required to support Least Concern assessments, while a threatened rating still requires all relevant data). The new requirements split supporting data for Red List assessments into three categories:

1. **Required** – required for all Red List assessments or under specific conditions (e.g. plant growth form is only needed for plants).
2. **Recommended** – not mandatory, but assessors are encouraged to enter such data.
3. **Discretionary (Optional)** – includes data not essential for the Red List, but which may be recorded for analytical purposes.

Reduced data requirements for Least Concern species open up the possibility of rapidly documenting many plant species – see section 4.2 – potentially leading to a future increase in Least Concern assessments published on the Red List.

This revision of data-requirements highlights several important points. First, pressure from IUCN plant Specialist Groups helped make positive changes to Red Listing procedures; the Red List Committee (incorporating Red List partners) was willing to respond. Second, the changes are also helpful for other highly species-rich groups, such as fungi and invertebrates, that face similar challenges. Third, the Red List Committee should carefully consider which data are mandatory for Red Listing. New kinds of data will doubtless be required to support future Red List assessments, to document novel threats or support policy changes, but new data requirements should be clearly justified to the Red List community and tools or techniques should be developed to facilitate the generation of the new data.

2.3 Batch assessment upload with 'SIS Connect'

The data management system underpinning the Red List (SIS) was developed to allow manual entry of supporting data for Red List assessments. However, supporting data needed for assessments, such as country-level distributions, taxonomic data or specimen data, often already exist in other databases. The need to manually transfer these data from one system to another limits the rate at which assessments can be added to SIS. To speed up the process, the Red List Unit developed a system to simultaneously transfer multiple assessments to SIS through a web service called 'SIS Connect' (http://connect.iucnredlist.org/). Successful transfers have been made by the Royal Botanic Gardens, Kew (via the BRAHMS database), by the New Caledonia Plant Red List Authority and by the South African National Biodiversity Institute.

2.4 Inclusion of assessments in languages other than English

Until recently the Red List only published English-language assessments, despite IUCN's position of supporting three official languages (English, French and Spanish). Because of this, regional Red Listing initiatives generating assessments in French (UICN France et al., 2013), Portuguese (Martinelli et al., 2013) and Spanish (Calderón Saenz Eduardo, 2005) have not published their results on the global Red List, or have had to undertake expensive and time-consuming translations into English beforehand. This barrier constrained the potential connectivity between regional assessment initiatives and the global Red List, especially the submission to the Red List of assessments of national endemics, which are equivalent to global scale assessments (Rodríguez, 2008).

Assessments can now be submitted in French, Spanish and Portuguese. The potential gain to the Red List in terms of growth in non-English language assessments has yet to be quantified, but with French, Spanish and Portuguese being the primary languages in seven of the top 17 megadiverse countries, each containing more than 5,000 endemic plant species (Mittermeier and Goettsch, 1997), the majority of which are currently 'Not Evaluated', there is clearly scope for a large increase in assessments.

2.5 Spatial tools support Red List automation

Spatial metrics used in the Red List criteria that were previously challenging to calculate have now become mainstream through the development of spatial tools – see Table S4 for a list. These web based tools such as *GeoCAT* (Bachman et al., 2011), or R packages such as *Red* (Cardoso, 2017), can be used to calculate spatial metrics such as extent of occurrence (EOO) and area of occupancy (AOO) and build species distribution models using occurrence data. Advantages include rapid, consistent and auditable measurements. Disadvantages include potential uncritical user acceptance of results without considering other factors, such as sampling intensity (Sheth et al., 2012), although this can be addressed with training (see section 2.7).

2.6 Linking new species and Red List assessment publications

New plant species are described at a fairly consistent rate, with a mean of 2,205 per year (1999–2017, International Plant Names Index, 2018). However, recently described species are not being assessed and published on the Red List in a timely manner, usually taking more than 5 years after description (Figure 6).

Authors of species new to science often include statements on their conservation status. Journals such as *Kew Bulletin* request descriptions of new taxa to include conservation statements specifically applying the IUCN Red List categories and criteria. However, these assessments rarely reach the global Red List. Of the 1,234 newly described taxa published in *Kew Bulletin* from 2003–2017, only 116 (9%) had assessments on the Red List 2018.2. A disincentive could be the extra effort required to transfer data to SIS and lack of perceived 'reward' for publication on the Red List if it is not considered equivalent to a scientific journal. The recent registration of the Red List with an international standard serial number (ISSN 2307-8235), development of a journal-like submission process and decision to publish Red List assessments as PDFs with digital object identifiers (DOI), and a more dynamic publication schedule, will all help to address this perception and incentivise publication on the Red List.

The connection between new species descriptions and Red List assessments can also be improved with initiatives such as the 'Species Conservation Profile' (SCP) (Cardoso et al., 2016). The profile is equivalent to a Red List assessment, minus the final category and rationale. It can be published through the *Biodiversity Data Journal* (BDJ) and subsequently submitted for publication on the Red List via SIS Connect. We encourage other journals that publish species descriptions to adopt this approach and strengthen links between extinction risk assessments of new species and formal publication on the Red List.

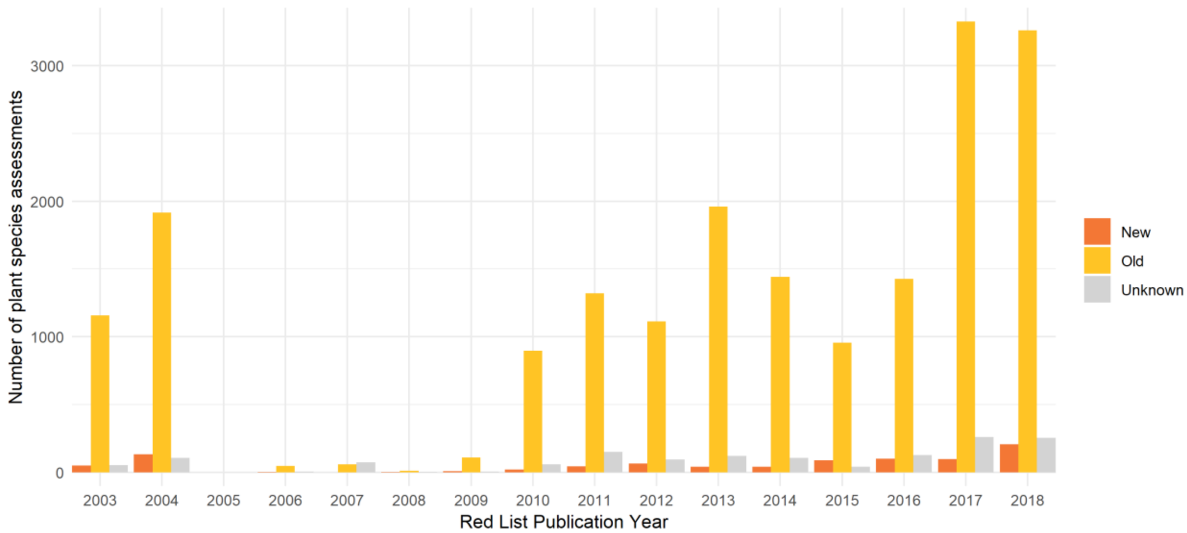


Figure 6 Number of plant species assessments documented on the Red List for each year from 2003 – 2018, grouped by the time since the species was described. Species that were documented on the Red List within 5 years of being published are labelled as 'New' and species where more than 5 years had elapsed before a Red List assessment was published are labelled as 'Old'. When the year of species description could not be found or was ambiguous, it is marked as 'Unknown'. As there are often multiple updates of the Red List in a year, the latest update was used to give the annual total for that year. There were no plant Red List assessments added to the Red List in 2005. Year of species description was derived from the International Plant Name Index (IPNI) (www.ipni.org). The year 2018 is likely to underestimate the number of described species as these may not have been indexed by IPNI yet.

2.7 Consolidated training resources

Although formal training is not necessary in order to submit an assessment, many plant Red List contributors have been trained in applying the Red List Categories and Criteria and documenting an assessment. A shortage of plant experts trained in Red Listing could be a limiting factor for global Red Listing, and has been highlighted as a problem for regional Red Listing (Miller et al., 2007). Options for self-study have been greatly enhanced by the release of an online training course. The "Assessing Species' Extinction Risk using IUCN Red List Methodology" course, available from the 'ConservationTraining' portal https://www.conservationtraining.org, was launched in April 2014, and enrolled 2,513 people by October 2016 (Caroline Pollock pers. comm.). Instructor-led training is also likely to grow the number of plant specialists contributing Red List assessments. Training should be targeted at scientists focused on areas of high plant diversity and offered in the most appropriate supported language. Training should also be followed up with a period of first-time assessment support as several sessions may be needed before assessment competency is attained (see section 4.3 for further support tools).

Currently, it is difficult to analyse the impact of Red List training because trainees are not adequately tracked. This could be resolved with ORCID identifiers, unique 16-digit numbers that unambiguously identify researchers (Haak et al., 2012). If Red List trainees sign up for ORCID identifiers and document Red List training as a qualification, it will be possible to link trainees with assessments, and quantify the impact of training on assessment activity. If language and keywords on geographic and taxonomic interest are also documented in ORCID, then the reach of training in other languages can be monitored and potential recruits to fill Specialist Group gaps can be identified (see section 3.3).

3. Challenges

3.1 Funding

Although the IUCN Red List is a critical conservation resource, its long-term stability could be compromised if core operating costs are not met. This has already been recognised in the Red List Strategic Plan (Result 9: The IUCN Red List is sufficiently and sustainably financed) (IUCN Red List Committee, 2013). In 2013, growing and maintaining the Red List cost US$4.7 million, plus the equivalent of US$0.5 million in volunteer time (Juffe-Bignoli et al., 2016). For a flagship product, this is small relative to IUCN's annual income of US$129 million (IUCN, 2017); Red List sustainability and growth may be at risk if funding is not prioritised to support vital infrastructure such as SIS, and to staff the Red List Unit sufficiently. Stabilising the core Red List operations, such as maintaining and developing SIS, quality control, standards development, training and support will ensure that additional funding can be wholly directed towards assessment and reassessment generation.

The only comprehensive evaluation to date (Juffe-Bignoli et al., 2016) revealed that philanthropy was the biggest source of Red List funding (42%), followed by governments (30%). The small (3%) contribution from the private sector can grow, and recent partnerships such as that with the Toyota Motor Company (https://www.iucn.org/content/new-iucn-toyota-partnership-expand-knowledge-threats-global-biodiversity) illustrate that large multi-nationals are willing to engage with the Red List. This commitment to tackle gaps in coverage such as for plants (http://www.kew.org/about/press-media/press-releases/toyota-supports-kew's-vital-research-threatened-plant-species) is a model that other multi-nationals can follow.

3.2 National and regional assessments for the global Red List

Many regional or national scale plant assessments have not been included in the global Red List. However, if IUCN categories and criteria have been applied and species are endemic to the region of assessment, then they are equivalent to global assessments and could be published on the Red List. A recent review of all digitally available plant conservation assessments revealed that 241,919 have been published (Bachman et al., 2017), representing 111,824 species, most of which were assessed using IUCN Red List criteria (see *ThreatSearch* to access assessment data [http://www.bgci.org/threat_search.php]). Approximately 60% of plant species are endemic to a single region (Bachman et al., 2017), indicating that a large potential source of global Red List assessments already exists. Barriers such as the need to translate (section 2.4) and difficulties with batch transfer (section 2.3) have now been resolved, but resources are still required to link regional assessments to the global Red List. In addition, a clear strategy is needed to engage the active community of regional assessors with the global Red List programme.

Global Red Listing of endemic plant species can be prioritised by cross-referencing regional or national assessments in *ThreatSearch* with checklists of plants in these areas. The establishment of a National Red List Working Group has also helped align national Red Listing initiatives with the IUCN Red List (Rodríguez, 2008) by focusing on training in the application of IUCN Regional Guidelines and building awareness of batch import options (section 3.4). Good communication between the IUCN Red List Programme and regional assessors is needed to ensure value is added to national/regional assessments by publishing them on the global Red List (Miller et al., 2007).

3.3 Supporting the Plant assessment champions –Specialist Groups and Authorities

Several large, important plant families (e.g. Asteraceae, Fabaceae, Lamiaceae, Poaceae, Rubiaceae) have no SG/RLA (Table S1 and S3); these should be targets for the development of new SG/RLAs. Geographically there are gaps in SG/RLA coverage in known plant diversity hotspots such as Central America, north-western South America, West Africa, and South-East Asia including plant mega-diversity countries such as Australia, India, Papua New Guinea, Peru, Philippines, Venezuela and Ecuador (Figure 7). Thus, many plant species fall outside the remit of any Specialist Group and steps must be taken to strategically establish more groups in these areas. The recent addition of the Indonesia RLA and Colombian SG and plans for a West African Plants RLA, a Sonoran Desert Plants SG and a Western Ghats Plant RLA, will all help address these gaps.

The SGs/RLAs are voluntary and built on goodwill. IUCN SSC should clearly specify incentives for experts to engage voluntarily with these groups, and should support those wishing to set up new groups through, for example, seed money, streamlining the application process, ensuring rapid decisions on proposals for new groups, and providing training on roles and responsibilities. Consolidating and supporting existing groups through training is also a priority.

Establishing more SGs and RLAs may mean greater overlap of jurisdiction. Although reviewing an assessment only requires one RLA, each relevant RLA should be informed of the assessment, and according to present guidelines has up to three months to review it (IUCN, 2016). This is intended to ensure robust review of Red List assessments, but could also delay the review process. To avoid bottlenecks caused by sequential reviews, we encourage RLAs with overlapping remits to review assessments in parallel where possible (e.g. within one three-month period), or if they are happy to do so, to cede responsibility to the best-placed RLA. A review provided by one RLA, that has been fully addressed by assessors, should be, and typically is, sufficient for publication of an assessment.

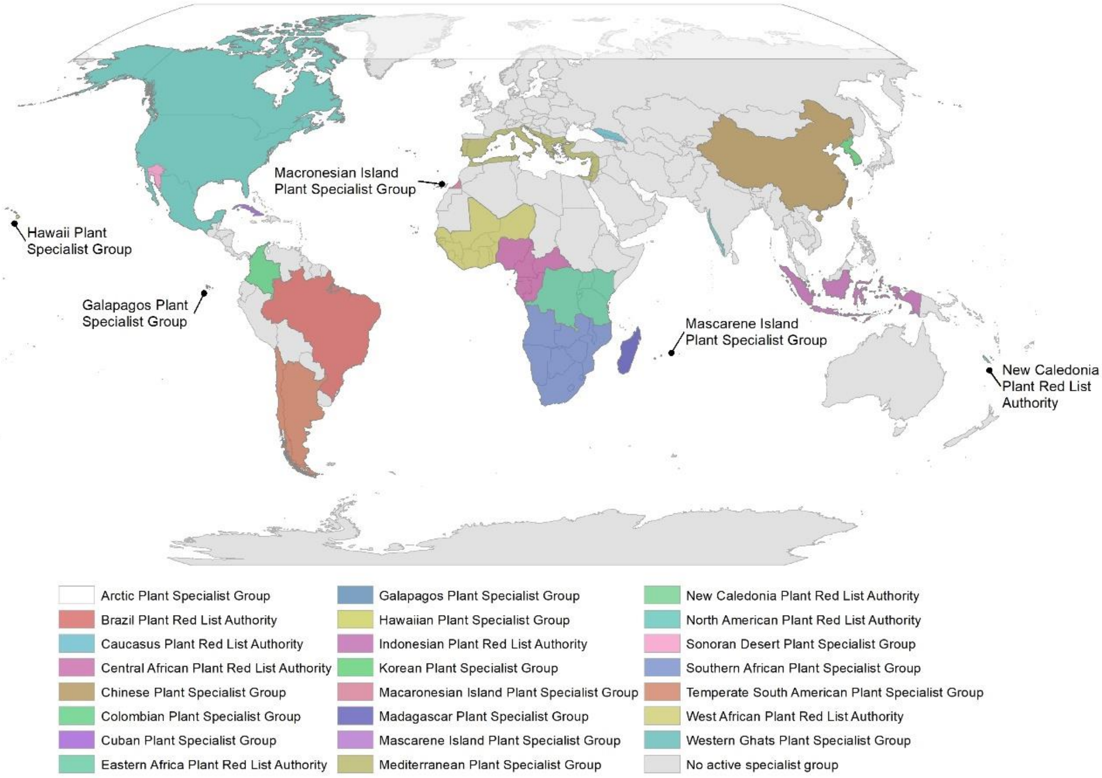


Figure 7. Coverage of the world by plant specialist groups (and Red List Authorities) with a geographic focus. The West African, Sonoran Desert and Western Ghats Plant Specialist Groups are in preparation.

3.4 Primary data

Botanical collections rarely incorporate demographic data, which is problematic because population size and population decline are core elements of the Red List criteria (IUCN, 2001). A single specimen collection could represent a single individual or thousands of individuals, which translates to plausible Red List categories of Critically Endangered to Least Concern. Gathering demographic data can be time-consuming and expensive, but mainstreaming population size estimation into field work will expand the options for plant Red List assessors and will lead to more robust assessments.

4. Opportunities

4.1 Automated documentation of Least Concern species

The manual nature of species assessment is a major factor limiting growth of the Red List, but automation is possible. Reduced data requirements (section 2.2) and batch assessment transfer options (section 2.3) have opened the possibility of scaling-up documentation of Least Concern assessments. Many required fields for Least Concern assessments, such as taxonomy, countries of occurrence and plant growth form, already exist in databases. We developed a tool using freely accessible data on plants to rapidly generate required data for LC assessments, including spatial points (https://XXXX.shinyapps.io/plantdash/). Crucially the assessor needs to determine which species should be assigned the LC category.

4.2 Prioritisation

Rapid, automatically generated assessments can save time and reduce costs for future assessments, but only if the species likely to be Least Concern are known. From a representative sample, we can infer that ~65% of plant species (~200,000) are likely to be Least Concern (Brummitt et al., 2015), but we don't know which. Species can be assigned a likely category using predictive models based on coarse geographic data (Darrah et al., 2017), occurrence data from herbarium specimens (Krupnick et al., 2009), climate data (Moat et al., 2018) and traits (Saatkamp et al., 2018). These approaches can reach high levels of accuracy (>96%) in predicting non-threatened species (Nic Lughadha et al., 2018).

4.3 Advancing techniques to assess threatened species

Threatened and Near Threatened plants also need to be rapidly and robustly assessed to fill Red List knowledge gaps, but have greater data requirements than LC assessments. Using remotely sensed (or Earth Observation) data can speed up the process. Such data may currently be underutilised (Turner et al., 2015), and insufficiently complete, available, up-to-date, repeated or accurate for use in threat assessments (Joppa et al., 2016), but Earth Observation data on forest loss have been used successfully to infer population declines for Red List assessment (Buchanan et al., 2008; Tracewski et al., 2016). Inference of population declines for use in Red List assessments can also be achieved by applying statistical techniques to opportunistic occurrence data (Maes et al., 2015), provided that appropriate methods are used (Isaac et al., 2014).

The Red Listing process can also be improved with existing tools (Table S4). Online consultation via web-based *fora* has proven a more cost-effective approach to Red List assessments than in-person workshops (Rondinini et al., 2013). A web-based community approach could also help transfer Red List assessment knowledge from experienced to less-experienced assessors via social Q&A platforms, such as those hosted by Stack Exchange [https://stackexchange.com]. New techniques such as chatbots could provide automated support. Sharing knowledge in a way that is open to all should yield higher quality assessments and more efficient transfer to the Red List, as well as alleviating pressure on the Red List Unit as the main information resource for assessors.

4.4. Monitoring progress

What is the evidence that the actions already undertaken, or proposed in this review, can benefit the plant Red List? It is hard to tease apart the overlapping impact of different interventions. To monitor the envisaged growth, we developed a data dashboard that will be updated as the Red List is updated: https://XXXX.shinyapps.io/plantdash. The dashboard tracks where we expect growth in species assessments to occur such as Least Concern species, newly described species, endemic species, species assessed in a non-English language, and species within the remit of specialist groups such as trees.

Monitoring is already revealing areas of progress, for example, 509 assessments have been published on the Red List via the batch transfer SIS Connect system and 915 more are in the pre-publication processing stage (pers. comm. Craig Hilton-Taylor, 2018). Growth in SIS Connect use can be monitored to evaluate the benefit of this kind of technical development to the Red Listing process. If the rate of Red Listing does not increase, potential reasons should be investigated, such as insufficient capacity of the Red List Unit to process SIS Connect assessments, quality of documentation on the system or lack of awareness of its capabilities amongst the Red List community.

Growth in the use of assessments in languages other than English is already apparent with 20 plant assessments from Brazil, written in Portuguese, successfully published on the Red List in 2016. The most recent Red List updates include 57 assessments in French and two in Spanish (Castilian).

To date there have been 9 SCP papers published by BDJ, covering 195 taxa. Encouragingly, these include Red List knowledge gap groups such as Plantae, Aranae, Lepidoptera and Coleoptera. However, technical issues still need to be resolved and so far no SCPs have been transferred via the SIS Connect system (pers. comm. Craig Hilton-Taylor, 2018). If these issues can be overcome, other journals publishing new plant species descriptions can adopt similar strategies and utilise SIS Connect to help populate the Red List.

Progress is likely to result from a combination of factors that collectively will have impact, rather like the stabilization 'wedges' proposed for moving from business-as-usual to a stable emissions scenario in response to climate change (Pacala and Socolow, 2004).

5. Conclusion

We have demonstrated that although positive steps have been taken to grow the Red List of vascular plants, the rate of new assessments has yet to achieve levels that would be needed to reach goals set out in like the Barometer of Life, such as a 10-fold increase in annual assessment output. This may be due to a lag after new opportunities have been available, such as extending assessment language options, and as new methods are adopted, such as batch assessment upload.

In the drive to grow the Red List further, we have highlighted how several possible quick wins could be achieved (e.g. automation of Least Concern assessments), as well as key investment needs for future growth of the Red List (e.g. training and capacity building and supporting core operating costs of the Red List). Most of our findings are also applicable to other species-rich groups, that are under-represented on the Red List, although these will bring unique challenges (Cardoso et al., 2011).

We hope to stimulate further discussion on the challenge of expanding the Red List in a strategic and cost-effective way that remains scientifically robust. In an era of intensifying threats, it is urgent that we work towards as complete a Red List as possible, to support species conservation. Success in this endeavour will be a product of the ongoing and strengthening collaboration between IUCN and the Red List assessment community.

6. Acknowledgements

Alan Paton provided useful comments on an earlier version of this paper. Craig Hilton-Taylor provided summary statistics from the Red List Unit and commented on an earlier version of this manuscript. Caroline Pollock provided data on online training from Conservation Training. Cátia Canteiro, Helen Chadburn, Colin Clubbe, Lauren Gardiner, Serene Hargreaves, Justin Moat, Malin Rivers, Matthew Smith and Emma Williams provided useful discussion on the Red List assessment process. Stephen Davis, Chris Leon and Hugh Synge provided input on an earlier version of this manuscript. Heather Linden and Nicky Nicholson provided advice on handling IPNI names. We are grateful to members of the IUCN Plant Conservation Sub-Committee for providing the backdrop and inspiration for many of the issues discussed in this manuscript.

Reference

Bachman, S.P., Moat, J., Hill, A., De La Torre, J., Scott, B., 2011. Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. Zookeys 150, 117. https://doi.org/10.3897/zookeys.150.2109

Bachman, S.P., Nic Lughadha, E.M., Rivers, M.C., 2017. Quantifying progress toward a conservation assessment for all plants. Conserv. Biol. https://doi.org/10.1111/cobi.13071

Bennun, L., Regan, E.C., Bird, J., van Bochove, J.-W., Katariya, V., Livingstone, S., Mitchell, R., Savy, C., Starkey, M., Temple, H., Pilgrim, J.D., 2018. The Value of the IUCN Red List for Business Decision-Making. Conserv. Lett. 11, e12353. https://doi.org/10.1111/conl.12353

Bland, L.M., Collen, B., Orme, C.D.L., Bielby, J., 2015. Predicting the conservation status of data-deficient species. Conserv. Biol. 29, 250–259. https://doi.org/10.1111/cobi.12372

Boyd, C., Brooks, T.M., Butchart, S.H.M., Edgar, G.J., Da Fonseca, G. a. B., Hawkins, F., Hoffmann, M., Sechrest, W., Stuart, S.N., Van Dijk, P.P., 2008. Spatial scale and the conservation of threatened species. Conserv. Lett. 1, 37–43. https://doi.org/10.1111/j.1755-263X.2008.00002.x

Brummitt, N., Bachman, S., Moat, J., 2008. Applications of the IUCN Red List: towards a global barometer for plant diversity. Endanger. Species Res. https://doi.org/10.3354/esr006127

Brummitt, N.A., Bachman, S.P., Griffiths-Lee, J., Lutz, M., Moat, J.F., Farjon, A., Donaldson, J.S., Hilton-Taylor, C., Meagher, T.R., Albuquerque, S., Aletrari, E., Andrews, A.K., Atchison, G., Baloch, E., Barlozzini, B., Brunazzi, A., Carretero, J., Celesti, M., Chadburn, H., Cianfoni, E., Cockel, C., Coldwell, V., Concetti, B., Contu, S., Crook, V., Dyson, P., Gardiner, L., Ghanim, N., Greene, H., Groom, A., Harker, R., Hopkins, D., Khela, S., Lakeman-Fraser, P., Lindon, H., Lockwood, H., Loftus, C., Lombrici, D., Lopez-Poveda, L., Lyon, J., Malcolm-Tompkins, P., McGregor, K., Moreno, L., Murray, L., Nazar, K., Power, E., Quiton Tuijtelaars, M., Salter, R., Segrott, R., Thacker, H., Thomas, L.J., Tingvoll, S., Watkinson, G., Wojtaszekova, K., Nic Lughadha, E.M., 2015. Green Plants in the Red: A Baseline Global Assessment for the IUCN Sampled Red List Index for Plants. PLoS One 10, e0135152. https://doi.org/10.1371/journal.pone.0135152

Buchanan, G.M., Butchart, S.H.M., Dutson, G., Pilgrim, J.D., Steininger, M.K., Bishop, K.D., Mayaux, P., 2008. Using remote sensing to inform conservation status assessment: Estimates of recent deforestation rates on New Britain and the impacts upon endemic birds. Biol. Conserv. 141, 56–66. https://doi.org/10.1016/j.biocon.2007.08.023

Calderón Saenz Eduardo, 2005. Libro Rojo de plantas de Colombia, Libro rojo de plantas de Colombia. Volumen 2. Palmas, frailejones y zamias. Serie Libros Rojos de Especies Amenazadas de Colombia.

Cardoso, P., 2017. red - an R package to facilitate species red list assessments according to the IUCN criteria. Biodivers. Data J. 5, e20530. https://doi.org/10.3897/BDJ.5.e20530

Cardoso, P., Erwin, T.L., Borges, P.A.V., New, T.R., 2011. The seven impediments in invertebrate conservation and how to overcome them. Biol. Conserv. 144, 2647–2655. https://doi.org/10.1016/j.biocon.2011.07.024

Cardoso, P., Stoev, P., Georgiev, T., Senderov, V., Penev, L., 2016. Species Conservation Profiles compliant with the IUCN Red List of Threatened Species. Biodivers. Data J. 4, e10356. https://doi.org/10.3897/BDJ.4.e10356

Clausnitzer, V., Kalkman, V.J., Ram, M., Collen, B., Baillie, J.E.M., Bedjanič, M., Darwall, W.R.T., Dijkstra, K.-D.B., Dow, R., Hawking, J., Karube, H., Malikova, E., Paulson, D., Schütte, K., Suhling, F., Villanueva, R.J., von Ellenrieder, N., Wilson, K., 2009. Odonata enter the biodiversity crisis debate: The first global assessment of an insect group. Biol. Conserv. 142, 1864–1869. https://doi.org/10.1016/j.biocon.2009.03.028

Darrah, S.E., Bland, L.M., Bachman, S.P., Clubbe, C.P., Trias-Blasi, A., 2017. Using coarse-scale species distribution data to predict extinction risk in plants. Divers. Distrib. 23, 435–447. https://doi.org/10.1111/ddi.12532

Faith, D.P., 1992. Conservation evaluation and phylogenetic diversity. Biol. Conserv. 61, 1–10. https://doi.org/10.1016/0006-3207(92)91201-3

Grenyer, R., Orme, C.D.L., Jackson, S.F., Thomas, G.H., Davies, R.G., Davies, T.J., Jones, K.E., Olson, V.A., Ridgely, R.S., Rasmussen, P.C., Ding, T.-S., Bennett, P.M., Blackburn, T.M., Gaston, K.J., Gittleman, J.L., Owens, I.P.F., 2006. Global distribution and conservation of rare and threatened vertebrates. Nature 444, 93–96.

Guiry, M.D., Guiry, G.M., 2019. AlgaeBase [WWW Document]. World-wide Electron. Publ. Natl. Univ. Ireland, Galway. URL http://www.algaebase.org (accessed 2.15.19).

Haak, L.L., Fenner, M., Paglione, L., Pentz, E., Ratner, H., 2012. ORCID: A system to uniquely identify researchers. Learn. Publ. 25, 259–264. https://doi.org/10.1087/20120404

Hayward, M.W., Child, M.F., Kerley, G.I.H., Lindsey, P.A., Somers, M.J., Burns, B., 2015. Ambiguity in guideline definitions introduces assessor bias and influences consistency in IUCN Red List status assessments. Front. Ecol. Evol. 3, 87. https://doi.org/10.3389/fevo.2015.00087

Howard, S.D., Bickford, D.P., 2014. Amphibians over the edge: silent extinction risk of Data Deficient species. Divers. Distrib. 20, 837–846. https://doi.org/10.1111/ddi.12218

IFC, 2012. Performance Standard 6 Biodiversity Conservation and Sustainable Management of Living Natural Resources [WWW Document]. URL http://www.ifc.org/wps/wcm/connect/bff0a28049a790d6b835faa8c6a8312a/PS6_English_2012.pdf?MOD=AJPERES

International Plant Names Index, 2018. International Plant Names Index [WWW Document]. URL http://www.ipni.org/ (accessed 7.10.18).

Isaac, N.J.B., van Strien, A.J., August, T.A., de Zeeuw, M.P., Roy, D.B., 2014. Statistics for citizen science: extracting signals of change from noisy ecological data. Methods Ecol. Evol. 5, 1052–1060. https://doi.org/10.1111/2041-210X.12254

IUCN, 2018a. Table 1: Numbers of threatened species by major groups of organisms (1996–2018) [WWW Document]. URL http://cmsdocs.s3.amazonaws.com/summarystats/2018-2_Summary_Stats_Page_Documents/2018_2_RL_Stats_Table_1.pdf

IUCN, 2018b. SIS Self-teach Tool [WWW Document]. URL http://www.iucnredlist.org/technical-documents/red-list-training/species-information-service

IUCN, 2017. IUCN 2016 Annual Report. Gland, Switzerland.

IUCN, 2016. Rules of Procedure for IUCN Red List Assessments 2017–2020.

IUCN, 2001. IUCN Red List Categories and Criteria: version 3.1. Prep. by IUCN Species Surviv. Comm.

IUCN Red List Committee, 2013. The IUCN Red List of Threatened Species: Strategic Plan 2013 - 2020.

Jarić, I., Roberts, D.L., Gessner, J., Solow, A.R., Courchamp, F., 2017. Science responses to IUCN Red Listing. PeerJ 5, e4025. https://doi.org/10.7717/peerj.4025

Joppa, L.N., O'Connor, B., Visconti, P., Smith, C., Geldmann, J., Hoffmann, M., Watson, J.E.M., Butchart, S.H.M., Virah-Sawmy, M., Halpern, B.S., Ahmed, S.E., Balmford, A., Sutherland, W.J., Harfoot, M., Hilton-Taylor, C., Foden, W., Minin, E.D., Pagad, S., Genovesi, P., Hutton, J., Burgess, N.D., 2016. Filling in biodiversity threat gaps. Science (80-.). 352, 416–418. https://doi.org/10.1126/science.aaf3565

Joppa, L.N., Roberts, D.L., Pimm, S.L., 2010. How many species of flowering plants are there? Proc. R. Soc. B Biol. Sci. 554–559. https://doi.org/10.1098/rspb.2010.1004

Juffe-Bignoli, D., Brooks, T.M., Butchart, S.H.M., Jenkins, R.B., Boe, K., Hoffmann, M., Angulo, A., Bachman, S., Böhm, M., Brummitt, N., Carpenter, K.E., Comer, P.J., Cox, N., Cuttelod, A., Darwall, W.R.T., Di Marco, M., Fishpool, L.D.C., Goettsch, B., Heath, M., Hilton-Taylor, C., Hutton, J., Johnson, T., Joolia, A., Keith, D.A., Langhammer, P.F., Luedtke, J., Nic Lughadha, E., Lutz, M., May, I., Miller, R.M., Oliveira-Miranda, M.A., Parr, M., Pollock, C.M., Ralph, G., Rodríguez, J.P., Rondinini, C., Smart, J., Stuart, S., Symes, A., Tordoff, A.W., Woodley, S., Young, B., Kingston, N., 2016. Assessing the Cost of Global Biodiversity and Conservation Knowledge. PLoS One 11, e0160640. https://doi.org/10.1371/journal.pone.0160640

Krupnick, G.A., Kress, W.J., Wagner, W.L., 2009. Achieving Target 2 of the Global Strategy for Plant Conservation: Building a preliminary assessment of vascular plant species using data from herbarium specimens. Biodivers. Conserv. 18, 1459–1474. https://doi.org/10.1007/s10531-008-9494-1

Larsen, F.W., Bladt, J., Balmford, A., Rahbek, C., 2012. Birds as biodiversity surrogates: will supplementing birds with other taxa improve effectiveness? J. Appl. Ecol. 49, 349–356. https://doi.org/10.1111/j.1365-2664.2011.02094.x

Mace, G., Collar, N.J., Gaston, K.J., Hilton-Taylor, C., Akakaya, H.R., Leader-Williams, N., Milner-Gulland, E.J., Stuart, S.N., 2008. Quantification of extinction risk: IUCN's system for classifying threatened species. Conserv. Biol.

Mace, G.M., Lande, R., 1991. Assessing Extinction Threats : Toward a Reevaluation of IUCN Treatened Species Categories. Conserv. Biol. 5, 148–157.

Maes, D., Isaac, N.J.B., Harrower, C.A., Collen, B., van Strien, A.J., Roy, D.B., 2015. The use of opportunistic data for IUCN Red List assessments. Biol. J. Linn. Soc. n/a-n/a. https://doi.org/10.1111/bij.12530

Marsh, H., Dennis, A., Hines, H., Kutt, A., McDonald, K., Weber, E., Williams, S., Winter, J., 2007. Optimizing allocation of management resources for wildlife. Conserv. Biol. 21, 387–399. https://doi.org/10.1111/j.1523-1739.2006.00589.x

Martinelli, G., Moraes, M., Botânico, J., Janeiro, R. de, 2013. Livro vermelho da flora do Brasil.

Miller, R.M., Rodríguez, J.P., Aniskowicz-Fowler, T., Bambaradeniya, C., Boles, R., Eaton, M.A., Gärdenfors, U., Keller, V., Molur, S., Walker, S., Pollock, C., 2007. National threatened species listing based on IUCN criteria and regional guidelines: current status and future perspectives. Conserv. Biol. 21, 684–96. https://doi.org/10.1111/j.1523-1739.2007.00656.x

Mittermeier, R.A., Goettsch, C.M., 1997. Megadiversity: Earth's Biologically Wealthiest Nations, CEMEX Conservation Book Series. https://doi.org/10.1111/j.1744-7429.2007.00368.x

Moat, J.F., Gole, Tadesse, W., Davis, Aaron, P., 2018. Least concern to endangered: Applying climate change projections profoundly influences the extinction risk assessment for wild Arabica coffee. Glob. Chang. Biol. https://doi.org/10.1111/gcb.14341

Nic Lughadha, E., Walker, B.E., Canteiro, C., Chadburn, H., Davis, A.P., Hargreaves, S., Lucas, E.J., Schuiteman, A., Williams, E., Bachman, S.P., Baines, D., Barker, A., Budden, A.P., Carretero, J., Clarkson, J.J., Roberts, A., Rivers, M.C., 2018. The use and misuse of herbarium specimens in evaluating plant extinction risks. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 374, 20170402. https://doi.org/10.1098/rstb.2017.0402

Nic Lughadha, E.M., Govaerts, R., Belayaeva, I., Black, N., Lindon, H., Allkin, R., Magill, R.E., Nicholson, N., 2016. Counting counts: revised estimates of numbers of accepted species of flowering plants, seed plants, vascular plants and land plants with a review of other recent estimates. Phytotaxa 272, 82–88.

Pacala, S., Socolow, R., 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305, 968–72. https://doi.org/10.1126/science.1100103

Ricketts, T.H., Dinerstein, E., Boucher, T., Brooks, T.M., Butchart, S.H.M., Hoffmann, M., Lamoreux, J.F., Morrison, J., Parr, M., Pilgrim, J.D., Rodrigues, A.S.L., Sechrest, W., Wallace, G.E., Berlin, K., Bielby, J., Burgess, N.D., Church, D.R., Cox, N., Knox, D., Loucks, C., Luck, G.W., Master, L.L., Moore, R., Naidoo, R., Ridgely, R., Schatz, G.E., Shire, G., Strand, H., Wettengel, W., Wikramanayake, E., 2005. Pinpointing and preventing imminent extinctions. PNAS 102, 18497–18501. https://doi.org/www.pnas.org_cgi_doi_10.1073_pnas.0509060102

Rodrigues, A.S.L., Brooks, T.M., 2007. Shortcuts for Biodiversity Conservation Planning: The Effectiveness of Surrogates. Annu. Rev. Ecol. Evol. Syst. https://doi.org/10.1146/annurev.ecolsys.38.091206.095737

Rodrigues, A.S.L., Pilgrim, J.D., Lamoreux, J.F., Hoffmann, M., Brooks, T.M., 2006. The value of the IUCN Red List for conservation. Trends Ecol. Evol. 21, 71–6. https://doi.org/10.1016/j.tree.2005.10.010

Rodríguez, J.P., 2008. National Red Lists: The largest global market for IUCN Red List Categories and Criteria. Endanger. Species Res. 6, 193–198. https://doi.org/10.3354/esr00129

Rondinini, C., Di Marco, M., Visconti, P., Butchart, S.H.M., Boitani, L., 2013. Update or outdate: long-term viability of the IUCN Red List. Conserv. Lett. 7, n/a-n/a. https://doi.org/10.1111/conl.12040

Saatkamp, A., Affre, L., Dutoit, T., Poschlod, P., 2018. Plant traits and population characteristics predict extinctions in a long-term survey of Mediterranean annual plants. Biodivers. Conserv. 27, 2527–2540. https://doi.org/10.1007/s10531-018-1551-9

Sheth, S.N., Lohmann, L.G., Distler, T., Jiménez, I., Sheth, S.N., 2012. Understanding bias in geographic range size estimates. Glob. Ecol. Biogeogr. 21, 732–742. https://doi.org/10.1111/j.1466-8238.2011.00716.x

Stuart, S.N., Wilson, E.O., McNeely, J.A., Mittermeier, R.A., Rodríguez, J.P., 2010. Ecology. The barometer of life. Science 328, 177.

Symes, W.S., Edwards, D.P., Miettinen, J., Rheindt, F.E., Carrasco, L.R., 2018. Combined impacts of deforestation and wildlife trade on tropical biodiversity are severely underestimated. Nat. Commun. In press, 4052. https://doi.org/10.1038/s41467-018-06579-2

Tracewski, Ł., Butchart, S.H.M., Marco, M. Di, Ficetola, G.F., Rondinini, C., Symes, A., Wheatley, H., Beresford, A.E., Buchanan, G.M., 2016. Toward quantification of the impact of 21(st) -century deforestation on the extinction risk of terrestrial vertebrates. Conserv. Biol. https://doi.org/10.1111/cobi.12715

Turner, W., Rondinini, C., Pettorelli, N., Mora, B., Leidner, A.K., Szantoi, Z., Buchanan, G., Dech, S., Dwyer, J., Herold, M., Koh, L.P., Leimgruber, P., Taubenboeck, H., Wegmann, M., Wikelski, M., Woodcock, C., 2015. Free and open-access satellite data are key to biodiversity conservation. Biol. Conserv. 182, 173–176. https://doi.org/10.1016/j.biocon.2014.11.048

UICN France, CBNM, FCBN, MNHN, 2013. La Liste rouge des espèces menacées en France - Chapitre Flore vasculaire de La Réunion. Paris.

Venter, O., Fuller, R. a, Segan, D.B., Carwardine, J., Brooks, T., Butchart, S.H.M., Di Marco, M., Iwamura, T., Joseph, L., O'Grady, D., Possingham, H.P., Rondinini, C., Smith, R.J., Venter, M., Watson, J.E.M., 2014. Targeting global protected area expansion for imperiled biodiversity. PLoS Biol. 12, e1001891. https://doi.org/10.1371/journal.pbio.1001891

Progress, challenges and opportunities for Red Listing

Supporting information

Table S1. List of Plant Specialist Groups (SGs) and Red List Authorities (RLAs)

Table S2. Importance of taxonomic SG/RLAs for Red List assessment

Table S3. List of families with total number of species and proportion assessed on the Red List. (attached Excel sheet)

Figure S3. Chart (embedded in Table S3) showing proportion of species in each family that have been assessed against the number of species in each family. Taxonomic Specialist Groups and Red List Authorities are highlighted in solid points, all other families are shown with hollow points. Both x and y axes are on a logarithmic scale (base 10).

Table S4. List of spatial tools and technology useful for Red List assessments

References.

Nic Lughadha, E.M. et al., 2016. Counting counts: revised estimates of numbers of accepted species of flowering plants, seed plants, vascular plants and land plants with a review of other recent estimates. *Phytotaxa*, 272(1), pp.82–88.

Tracewski, Ł. et al., 2016. Toward quantification of the impact of 21(st) -century deforestation on the extinction risk of terrestrial vertebrates. *Conservation biology : the journal of the Society for Conservation Biology*. Available at: http://www.ncbi.nlm.nih.gov/pubmed/26991445 [Accessed April 6, 2016].

Code repository: https://github.com/stevenpbachman/RedList_Challenges

Table S1.

List of existing Plant specialist groups and authorities including status.

https://www.iucn.org/ssc-groups/plants-fungi

Group	Type	Status	Megadiverse Country
Arabian Plant Specialist Group	Geographic	Not active	
Arctic Plant Specialist Group	Geographic	Active	
Brazil Plant Red List Authority	Geographic	Active	Yes [Brazil]
Bryophyte Specialist Group (mosses, liverworts, and hornworts)	Taxonomic	Active	
Cactus and Succulent Plant Specialist Group	Taxonomic	Active	
Carnivorous Plant Specialist Group	Thematic	Active	
Caucasus Plant Red List Authority	Geographic	Active	
Central African Plant Red List Authority	Geographic	Active	
Chinese Plant Specialist Group	Geographic	Active	Yes [China]
Colombian Plant Specialist Group	Geographic	Newly established	Yes [Colombia]
Conifer Specialist Group	Taxonomic	Active	
Crop Wild Relative Specialist Group	Thematic	Active	
Cuban Plant Specialist Group	Geographic	Active	
Cycad Specialist Group	Taxonomic	Active	
Eastern Africa Plant Red List Authority	Geographic	Active	Yes [DRC Congo]
Freshwater Plant Specialist Group	Thematic	Active	
Galapagos Plant Specialist Group	Geographic	Active	
Global Trees Specialist Group	Thematic	Active	
Hawaiian Plant Specialist Group	Geographic	Active	
Indian Subcontinent Plant Specialist Group	Geographic	Not active	
Indonesian Plant Red List Authority	Geographic	Newly established	Yes [Indonesia]
Korean Plant Specialist Group	Geographic	Active	
Macaronesian Island Plant Specialist Group	Geographic	Active	
Madagascar Plant Specialist Group	Geographic	Active	Yes [Madagascar]
Mangrove Specialist Group	Thematic	Active	
Mascarene Island Plant Specialist Group	Geographic	Active	
Medicinal Plant Specialist Group	Thematic	Active	
Mediterranean Plant Specialist Group	Geographic	Active	
New Caledonia Plant Red List Authority	Geographic	Active	
North American Plant Red List Authority	Geographic	Active	Yes [USA]
Orchid Specialist Group	Taxonomic	Active	
Palm Specialist Group	Taxonomic	Active	
Seagrass Specialist Group	Taxonomic	Active	
Sonoran Desert Plants Specialist Group	Geographic	In preparation	Yes [USA]
Southern African Plant Specialist Group	Geographic	Active	Yes [South Africa]
Temperate South American Plant Specialist Group	Geographic	Active	
West African Plants Red List Authority	Geographic	In preparation	
Western Ghats Plant Red List Authority	Geographic	In preparation	Yes [India]

Table S2.

The number of described plants[1] that have received a Red List assessment[2], grouped by whether they fall under the remit of a taxonomic SG/RLA or not. Species under the remit of a SG/RLA were assessed more than you would expect by chance ($\chi 2 = 1241.2$, d.f. = 1, $p < 0.001$).

[1] The estimate of 417,801 is based on an estimated number of land plants (including vascular plants and bryophytes of 403,911) (Nic Lughadha et al., 2016), plus 6,637 species of green algae (Chlorophyta) and 7,253 red algae (Rhodophyta) (Guiry and Guiry, 2019).

[2] based on Red List version 2018-2

	# Red List Assessments	# Not Evaluated	Total	Proportion assessed
Species under remit of taxonomic SGs/RLAs	4,784	31,044	35,828	**13.3%**
Species outside the remit of taxonomic SGs/RLAs	22,730	359,243	381,973	**5.9%**
Total	**27,514**	**390,287**	**417,801**	

Table S4. A selection of tools and technology that could be used to support Red Listing.

Name	Tool/Data	Reference
GeoCAT	Web based tool for extent of occurrence (EOO) and area of occupancy (AOO) using online occurrence data	http://geocat.kew.org/
rCAT	Calculates extent of occurrence (EOO) and area of occupancy (AOO) using occurrence data.	https://cran.r-project.org/web/packages/rCAT/index.html
ConR	Calculates extent of occurrence (EOO) and area of occupancy (AOO) and other parameters	https://cran.r-project.org/web/packages/ConR/index.html
red	Calculates extent of occurrence (EOO), area of occupancy (AOO), mapping species ranges, species distribution modelling using climate and land cover and calculating the Red List Index for groups of species	https://cran.r-project.org/web/packages/red/index.html
downscale	Supports calculation of AOO by downscaling species occupancy at coarse grain sizes to predict species occupancy at fine grain sizes.	https://cran.r-project.org/web/packages/downscale/index.html
Google Earth Engine	Using deforestation rates as a surrogate for population declines	https://earthengine.google.com/ See also Tracewski et al. 2016
BioModelos	Platform to display species distribution models and elicit feedback from relevant experts	http://biomodelos.humboldt.org.co/
RedListR	Calculates extent of occurrence (EOO), area of occupancy (AOO), rate of change, and accounts for geometric uncertainty	https://cran.r-project.org/web/packages/redlistr/index.html
RedList Toolbox	Contains a series of tools to help with the RedList process, in ArcGIS	https://www.iucnredlist.org/
RAMAS red list/pro	Extent of occurrence, EOO (km²) Area of occupancy, AOO (km²) Trend in extent of occurrence (% per year) Trend in area of occupancy (% per year) Continuing decline in extent of occurrence Continuing decline in area of occupancy Extreme fluctuations in extent of occurrence Extreme fluctuations in area of occupancy	https://www.ramas.com/redlistpro

Paper 4. Extinction Risk – Horn of Africa Aloes

High extinction risk and conservation gaps for Aloe (Asphodelaceae) in the Horn of Africa

Status:

Second draft prepared. Awaiting feedback from co-authors before submission to the journal *Biodiversity and Conservation*.

Authorship statement:

Authors: **Bachman, S.P.**, Wilkin, P., Nordal, I,. Weber, O., Reader, T., Field, R., Demissew, S.

SB is lead author. SD provided supervision. SB, PW, OW, TR and SD conceived and designed the experiments, SB, PW, OW, IN and SD curated the data, SB performed the experiments and analysed the data, SB, PW, OW, IN, TR, RF and SD and wrote the paper.

High extinction risk and conservation gaps for *Aloe* (Asphodelaceae) in the Horn of Africa

Authors & Affiliations:

Steven P. Bachman[1,2]* s.bachman@kew.org orcid.org/0000-0003-1085-6075

Paul Wilkin[1] p.wilkin@kew.org

Inger Nordal[3] inger.nordal@mn.uio.no

Odile Weber[4] Odile.WEBER@mnhn.lu orcid.org/0000-0002-0861-2752

Tom Reader[2] Tom.Reader@nottingham.ac.uk

Richard Field[2] Richard.Field@nottingham.ac.uk orcid.org/0000-0003-2613-2688

Sebsebe Demissew[1,5]* - sebseb.demissew@gmail.com

[1]Royal Botanic Gardens, Kew, Richmond, Surrey, TW9 3AE, UK

[2]School of Geography, University of Nottingham, Nottingham, NG7 2RD, UK

[3]Department of Biology, University of Oslo, P.O. Box 1045, Blindern, N-0316, Oslo, Norway

[4]Recherche et collections, Musée national d'histoire naturelle, 25 rue Münster, L-2160 Luxembourg

[5]National Herbarium, College of Natural Sciences, Addis Ababa University, P.O. Box 3434, Addis Ababa, Ethiopia

*Author for correspondence

Acknowledgements

We would like to thank Craig Hilton-Taylor for co-ordinating the review and publication of the IUCN Red List assessments of aloes on the Red List website, include the review of some species. We also thank Henk Beentje on behalf of the East Africa Plant Red List Authority for additional reviews of assessments. SD would like to acknowledge the support from NUFU

(Norway for work on Aloes and Lilies, and the Carlsberg Foundation, Copenhagen for continued support for the study of the Ethiopian vegetation. Naomi Carvey provided data from the Millennium Seed Bank Data Warehouse.

Journal and article type:

Biodiversity and Conservation – Original research (9,000 words)

Keywords:

Red List, IUCN, Protected areas, Threats

Abstract

150-250 words

Identification of conservation priorities is essential for conservation planning, especially as the biodiversity crisis develops. We aimed to support conservation prioritisation by addressing knowledge gaps for the genus *Aloe* in the Horn of Africa. Specifically, we developed a dataset of herbarium voucher specimens and occurrence data to estimate geographic distribution of 88 species of *Aloe* and used this to estimate extinction risk and establish the major threats to *Aloe* in this region. The resulting assessments, each published on the IUCN Red List, show that 39% of the species are threatened with extinction, and the principal threats are the expansion and intensification of crop farming and livestock farming, gathering of plants, and unintentional effects of logging and wood harvesting. We review ex situ conservation in botanic gardens and seed banks, revealing gaps in coverage and urgent priorities for collection, with 25 threatened *Aloe* species currently unrepresented in seed banks.

Protected areas in the region offer limited coverage of *Aloe* distributions and the most recently designated areas are increasingly in regions that do not overlap with *Aloe* distributions. However, we show with a simple optimisation approach that even a modest increase in area of 824 square kilometres would allow representation of all *Aloe* species, although further data are needed to test the area required to ensure long-term persistence (resilience) of *Aloe* species.

Introduction

Human alteration of landscapes (Venter et al. 2016), unsustainable use of wild species

(Tierney et al. 2014), expansion and intensification of croplands (Kehoe et al. 2017) and increasing threats associated with a changing climate (Urban 2015) are all contributing factors to an ongoing biodiversity extinction crisis (Ceballos et al. 2015). Loss of species affects ecosystem function and can reduce biomass production, reduce stability of ecosystems and cause irreversible changes or even ecosystem collapse (Hooper et al. 2012; Cardinale et al. 2012; Newbold et al. 2018). With current spending on conservation deemed insufficient and inadequately allocated to bring about a halt to the global biodiversity crisis (McCarthy et al. 2012; Waldron et al. 2013), a process of prioritising conservation effort is necessary.

Numerous global-scale approaches have been developed to identify species and sites of greatest importance for conservation (Brooks et al. 2006) – including biodiversity hotspots (Myers et al. 2000), Key Biodiversity Areas (IUCN 2016a), Areas of Zero Extinction (AZEs, Ricketts et al. 2005) and Important Plant Areas (Darbyshire et al. 2017) – as well as approaches that prioritise conservation based on other factors such as evolutionary history (Li et al. 2018). Protecting these sites and associated species can be accomplished through the expansion of the protected area network (Butchart et al. 2012, 2015). This approach is consistent with global conservation targets such as the Convention on Biological Diversity's (CBD) Aichi Target 11 to conserve 17% of terrestrial land that is '…of particular importance for biodiversity…' (UNEP/CBD 2010) and the Global Strategy for Plant Conservation (GSPC) Target 5 that aims to conserve 'At least 75 per cent of the most important areas for plant diversity...' (CBD 2010). These prioritisation approaches depend on high-quality biodiversity data such as species inventories, species distribution maps and estimates of species' extinction risk.

Historically, biodiversity data collection has been biased towards areas of relatively low diversity, away from the tropics (Collen et al. 2008). Despite growth in digitally accessible information (DAI), such as primary observation data held in museums and herbaria (Meyer et al. 2016; Le Bras et al. 2017), there are still major gaps in coverage that need to be addressed, particularly in emerging economies (Meyer et al. 2015). Insufficient data coverage and biased data can affect performance of algorithms to select protected area networks (Grand et al. 2007), although even limited data can provide valuable information for evaluating complementarity during protected area selection (Gaston and Rodrigues 2003). Furthermore, a potential cost of waiting too long for a 'complete' dataset is that opportunities for protection can be missed (Grantham et al. 2009). Gaps are also prevalent in species-level conservation products such as the IUCN Red List of Threatened Species (hereafter 'Red List'). The Red List is both a quantitative system to classify extinction risk under prevailing conditions (IUCN 2012) and a dataset of assessed species with extinction risk ratings and associated data [https://www.iucnredlist.org/]. Although extinction risk of species should not be the sole consideration when prioritising conservation effort (Arponen 2012), it does reveal that we need to act urgently, in a way that is comparable across species; the Red List has been widely utilised in conservation prioritisation efforts (Hoffmann et al. 2008; Venter et al. 2014). Gaps in taxonomic coverage of the Red List include fungi (Dahlberg and Mueller 2011), invertebrates (Cardoso et al. 2011) and plants, the latter having only ~6% of species assessed and published on the IUCN Red List (IUCN 2018). Recognising these gaps, calls have been made to treble the representation of plants on the list from 2009 levels to nearly 40,000 species (Stuart et al. 2010). In response, some gaps have been filled with comprehensive assessment of charismatic plant groups such as cacti (Goettsch et al. 2015) and ongoing assessment of thematic groups such as trees (Rivers 2017), but most plant species have yet to be assessed and published on the Red List.

The Horn of Africa represents a target for addressing the baseline biodiversity and conservation data gaps already highlighted. The Horn of Africa is an area of global significance for biodiversity, with three biodiversity hotspots represented in the region (Horn of Africa, Eastern Afromontane, and Coastal forests of Eastern Africa; Mittermeier et al. 2004), and countries in this region have reported the need for baseline data as part of National Biodiversity Strategy and Action Plans (Ethiopian Biodiveristy Institue 2015; Ullah and Gadain 2016). Here, we focus on *Aloe* L. (Asphodelaceae subf. Asphodeloideae), an iconic and economically important succulent plant genus that exhibits high diversity in this region; we explore extinction risk, threats and conservation gaps.

The genus *Aloe* extends across Sub-Saharan Africa and reaches into the Arabian Peninsula. The regions of highest species richness are in southern and eastern Africa, including Madagascar and the Horn of Africa – all areas that coincide with biodiversity hotspots (Mittermeier et al. 2004) (Figure 1). *Aloe* species play an important role in supporting local livelihoods across their distribution range, with documented uses for medicine, foods and as ornamental plants (Demissew and Nordal 2010; Grace 2011). Local harvesting has been reported to be non-detrimental to populations in some areas (Bjorå et al. 2015), but commercial demand for succulent plants like *Aloe* has caused declines that have led to their listing on the Convention on International Trade in Endangered Species (CITES) to help ensure that trade does not threaten their survival (CITES-Secretariat 2016). Despite these measures, illegal harvesting of wild *Aloe* persists, as does the threat of habitat conversion for agriculture (Darkoh 2003).

Progress in assessing the extinction risk of the estimated 630 *Aloe* species (Klopper et al. 2013) has been slow, with only 43 (7%) having published assessments by the time of the 2010 update of the IUCN Red List. Assessments have been made through regional initiatives including the Red List of South African Plants (Raimondo et al. 2009). Of the 128 *Aloe* taxa assessed for the Red List of South African Plants, 20% were listed as threatened and a further 8% were listed as either ‘Rare’ or ‘Declining’. In Madagascar, a preliminary assessment using the latest IUCN categories and criteria classified 39% of species as being threatened with extinction, although half were regarded as having insufficient data to assess (Rakotoarisoa et al. 2014). Plants across Eastern Africa are being targeted for assessment by the Eastern African Plant Red List Authority (EAPRLA) (Luke et al. 2014) and good progress is being made with over 2,400 taxa assessed to date (H. Beentje pers. comm. 2017). EAPRLA have assessed 28 *Aloe* species to date, of which 70% were classified as threatened (H. Beentje pers. comm. 2017). Prior to the present study, the only region with high *Aloe* species richness that is yet to receive assessment of extinction risk within the genus is the Horn of Africa.

Our aim was to address conservation knowledge gaps for *Aloe* in the Horn of Africa and to explore opportunities for prioritising future conservation efforts. We established a baseline dataset of *Aloe* occurrences and used this to underpin an assessment of extinction risk using the IUCN Red List categories and criteria (IUCN 2012). We used the IUCN Red List Threats Classification Scheme (version 3.2), based on Salafsky et al. (2008), to identify the threatening processes acting on *Aloe* occurring in the Horn of Africa region. We then identified current gaps in conservation coverage for *Aloe*, both in terms of the storage of genetic material ex situ (i.e. representation in seed banks and botanic gardens), as well as in situ, in the form of representation of wild populations in the protected area network. We then developed an algorithm to explore scenarios to efficiently grow the protected area network, in order to represent part of every *Aloe* distribution in this region.

Methods

Study area

Our study includes all species of *Aloe* that occur in, but are not necessarily endemic to, the Horn of Africa region. We define the Horn of Africa to include Djibouti, Eritrea, Ethiopia, Somalia, Sudan and South Sudan, covering a combined area of 4,388,570 km^2 (Figure 2a). The study area overlaps the Eastern Afromontane, Coastal Forest of Eastern Africa and Horn of Africa biodiversity hotspots (Mittermeier et al. 2004). Somalia, Djibouti and parts of Eritrea and Ethiopia are characterised by high aridity. The central highlands of Ethiopia, with peaks reaching 4,000 m, are separated by the Rift Valley and have a more temperate climate, and a diversity of vegetation types (Lillesø et al. 2011). The diversity in climate and elevation in this region has led, over time, to richness in plant life forms and taxa.

Aloe occurrence data

Global geographic ranges of *Aloe* species from the Horn of Africa study area were estimated from a database of herbarium voucher specimens. We compiled the database after consulting the literature and the following herbaria: The Natural History Museum, UK (BM); University of Copenhagen, Denmark (C); Herbarium, Dar es Salaam, Tanzania (DSM); National Museums of Kenya, Kenya (EA); Addis Ababa University, Ethiopia (ETH); Centro

Studi Erbario Tropicale, Università degli Studi di Firenze, Italy (FT); Royal Botanic Gardens, Kew, UK (K); Botanical Museum, University of Oslo, Norway (O); Museum of Evolution, Uppsala, Sweden (UPS); South African National Biodiversity Institute, South Africa (PRE); Harare Botanic Garden, Zimbabwe (SRGH), and Naturalis, Netherlands (WAG). Herbarium codes follow Thiers (2015). The taxonomic treatments were verified by one of us (Demissew). The following species are not endemic to the study region and extend into west Africa, Kenya or Tanzania (Figure 2b): *A. calidophila*, *A. canarina*, *A. citrina*, *A. ellenbeckii*, *A. erensii*, *A. labworana*, *A. lateritia*, *A. macleayi*, *A. parvidens*, *A. rabaiensis*, *A.rivae*, *A. rugosifolia*, *A. ruspoliana*, *A. schweinfurthii*, *A. secundiflora*, *A. vituensis*, *A. wrefordii*.

Where geographical co-ordinates were reported on specimen labels, these were manually checked for typos or obvious errors (e.g. where latitude and longitude were switched). Where co-ordinates were not given, each specimen was georeferenced post-facto from the textual description of the locality derived from the label. Each specimen was assigned a geographic co-ordinate pair using a variety of online gazetteers such as Fuzzy Gazetteer [http://dma.jrc.it/services/fuzzyg/] and GeoNames [http://geonames.nga.mil/namesgaz/], as well as mapping tools such as Google Earth [https://www.google.com/earth/] and historical paper maps. Specimens that did not contain sufficient information to assign co-ordinates (e.g. those only recorded to country or province level) were not included in the spatial analysis. After removing duplicate records, the final clean dataset comprised 711 occurrence records, representing 88 species with a mean of 8 occurrences per species. Fieldwork by Demissew, Weber and collaborators has targeted under-sampled areas and has supplemented historical herbarium records, thereby improving both spatial and temporal coverage. As few as 15 specimens per species has been shown to be sufficient to correctly estimate range size for use in Red List assessments (Rivers et al. 2011). Where species are represented by fewer than 15 specimens, expert knowledge can supplement occurrence data so that geographic range can be estimated to minimum and maximum bounds.

Subsequent to the initial data collection and analysis, a number of additional *Aloe* names were found in the literature. These names are mostly recent discoveries and are often represented by only one or two specimen collections from single locations. As we have not been able to examine these materials, and the descriptions are not sufficient to separate these names from existing species, we have not included them in this analysis. For the full list of excluded names see the Table A1 in the supplementary material.

Red List assessment

To assess the global Red List status of all 88 *Aloe* species occurring in the Horn of Africa study area, we adopted a semi-automated approach that combines spatial analysis of occurrence data with expert knowledge (Wilkin et al. 2013; Rakotoarinivo et al. 2014; Brummitt et al. 2015). We utilised our database of occurrences to calculate two metrics relating to geographic range used in IUCN Red List criterion B for all 88 species: extent of occurrence (EOO) and area of occupancy (AOO). In line with current IUCN guidelines, we calculated EOO in km² from the minimum convex polygon (MCP) of all occurrence records thought to represent extant populations. We assumed that historical occurrences represented extant populations unless there was evidence to the contrary, such as the combination of habitat loss and no recent collections from the same area. The MCPs were calculated using the Conservation Assessment Tools (CATs) extension for ArcView GIS (Moat

2007) and the web application GeoCAT (Bachman et al. 2011). They did not exclude unsuitable habitat within the extent of the MCP (IUCN Standards And Petitions Subcommittee 2014; Joppa et al. 2016). For AOO, our approach was to overlay the occurrence data with a grid at the reference scale of 2 km × 2 km cells (each cell was 4 km squared) and sum the number of occupied cells by the area of the cells (IUCN 2012).

The relatively low number of occurrence records for many species (Figure 3) introduces uncertainty into the estimation of both EOO and AOO (Rivers et al. 2011). To minimise uncertainty, expert knowledge gained from extensive field surveys in the region was utilised to fill gaps in coverage from occurrence data. We reviewed the EOO and AOO range estimates for each species and adjusted them in cases where we know there are extant populations that are not represented by occurrence records in our database. Uncertainty was recorded as minimum and maximum values for EOO and AOO, with maximum values incorporating further adjustments based on knowledge of habitat preferences and elevation ranges of *Aloe* species. The EOO and AOO estimates were further refined by expert review during the Red List assessment review stage (see below) and the method of calculation for each species is documented in Table A2 in the supplementary data.

The EOO and AOO values formed the basis of an assessment using IUCN Red List criterion B (restricted geographic ranges), but additional sub-criteria need to be met in order to complete a full assessment. We used the geographic range data and expert knowledge of threats in the region to estimate the number of threat-defined locations for each species and whether or not there was evidence for a continuing decline in any of the following: i) extent of occurrence; ii) area of occupancy; iii) area, extent and/or quality of habitat; iv) number of locations or subpopulations, or v) number of mature individuals (IUCN 2012). We also considered all other Red List criteria A, C, D and E, but insufficient data on population size or trends in populations over time were available to apply these criteria for most species, although *A. cremnophila* was assessed using criterion D as population size was estimated. The full Red List criteria are provided in Table A3 in the supplementary data. Once we had finished each assessment and determined the Red List rating, we entered the required data into the IUCN SIS data management system [https://sis.iucnsis.org]. All assessments were then reviewed by the East African Plant Red List Authority (EAPRLA) and the Red List Unit (Cambridge, UK). Once final modifications had been made, based on comments received through the review process, we re-submitted the assessments and supporting distribution maps for publication on the Red List website [www.iucnredlist.org]. Our assessments have thus become part of the Red List.

Classification of threatening processes

Specimen label data, literature searching, and expert judgement were used to code threats to each species using Threats Classification Scheme Version 3.2 (see Table A4 in the supplementary data for the full scheme). Threats to species were coded to the lowest level in the hierarchical classification scheme (e.g. 2. Agriculture & aquaculture > 2.3. Livestock farming & ranching > 2.3.2. Small-holder grazing, ranching or farming). Where species were affected by more than one threatening process, each threat was coded.

Coincidence of Protected Areas and Horn of Africa Aloes

We investigated the patterns and trends in protected area (PA) coverage in relation to the ranges of *Aloe* species occurring in the Horn of Africa. For this, and all further analysis, we used our *Aloe* point occurrence data as the basis for *Aloe* distribution ranges, which do not include the input of expert knowledge. Although expert knowledge was incorporated for EOO and AOO estimation, it was not mapped; therefore only the point occurrence data were used for analysis.

For protected areas we used the World Database on Protected Areas (WDPA) dataset (UNEP-WCMC and IUCN 2018), which was subset to the following countries that coincide with Horn of Africa *Aloe* distributions: Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Kenya, Nigeria, Somalia, South Sudan, Sudan, Tanzania, Togo and Uganda. Protected areas were not clipped to country boundaries. We excluded all PAs that were not coded as 'designated', did not have a designation year and/or did not have a reported area. WDPA protected areas are mapped with polygons and points; points are used when the PA boundary has not been formally determined. To enable spatial analysis of PAs and *Aloe* distributions, a circular buffer was generated around each PA point, equal to the size of the reported area of the PA. The polygon layer represented the minimum PA coverage and merging the polygon layer with the buffered point layer produced the maximum PA coverage.

To determine the number of *Aloe* species with ranges overlapping the PA network, and how this has changed over time, we buffered the *Aloe* point distributions for each species and intersected the buffered range with the PA network. We explored the impact of different buffer distances (2 km, 5 km, 10 km and 20 km) on overall results and compared them with published recommendations (Di Marco et al. 2017). We assumed the points represented stable populations over time and compared this with the PA network as it changed over time. We intersected the buffered point distributions with the PA network at each year where PA data were available. We also determined the extent to which *Aloe* species ranges overlap the PA network (proportion of range as derived from the 2, 5, 10 and 20 km buffers, respectively).

Extending the protected area network

To explore how the PA network could be extended to ensure that each species of *Aloe* is represented in a PA, we developed a simple greedy algorithm (Figure 4). The algorithm was designed to select a set of unprotected patches that represents all species in the smallest possible area. To do this, the entire *Aloe* occurrence dataset was buffered by 2 km and dissolved so that the overlapping buffers were merged into unique 'patches' of varying shapes and areas. We then identified the species that occurred in each patch. Then we identified patches that were completely contained within the current (2018) PA network and labelled these as protected patches. We labelled any species that occurred within a protected patch as protected. The remaining unprotected patches were analysed using the greedy algorithm to find the patch with the highest number of unprotected species. These species were then labelled as protected (representing adding this patch to the PA network). The algorithm repeated this process by finding the next patch with the highest number of species not included in the previous set of patches until all species are accounted for. When two patches had the joint highest number of species, one patch was randomly selected, meaning each iteration of the algorithm could have returned a different solution. The sum of patch area was reported after each iteration of the algorithm, but due to the random element of the algorithm, different iterations may produce a different minimum area. We tested how many iterations were needed to achieve the minimum total patch area. It was necessary to run the algorithm for 500 iterations to achieve a minimum value that was within 1kim of a minimum calculated based on 1,000 iterations. (see Table A5 in the supplementary data). We ran the algorithm 1,000 times with the target of achieving at least one patch protected for all species in the smallest area. We ran the algorithm separately for all species, and a combined subset of threatened and data deficient species. For the most area-efficient solution, we noted the full sequence of sites (see Table A6a and A6b in the supplementary information for all species and combined threatened and data deficient species, respectively) and mapped these.

Conservation collections in seed banks and botanic gardens

Finally, we explored the level of ex-situ conservation that *Aloe* species in the Horn of Africa were receiving. We queried the Botanic Gardens Conservation International (BGCI) PlantSearch database [https://www.bgci.org/plant_search.php] to determine how many collections of *Aloe* from the Horn of Africa there are across botanic gardens globally and if there is any difference in preference for threatened vs non-threatened *Aloes*. Similarly, we queried the Millennium Seed Bank base list [http://brahmsonline.kew.org/msbp/SeedData/BaseLists] to see how many *Aloe* species from the Horn of Africa have been seed collected and, again, whether there was any preference for threatened vs non-threatened species.

All analysis was performed in ArcGIS and R (R Core Team 2016; ESRI 2017) and further detail is provided in supplementary methods, along with R code to reproduce the analysis at: https://github.com/stevenpbachman/Aloes_Horn_Diversity

Results

Extinction risk of Aloes based on IUCN Red List assessments

Our assessment of *Aloe* from the Horn of Africa documented Red List status for 88 species, for which our best estimate is that 39% are threatened with a high risk of extinction (i.e. in the categories of Critically Endangered, Endangered or Vulnerable). Most of these are in the Endangered category (Table 1). The 'best' estimate takes into account the assumption that Data Deficient and data sufficient are equally threatened. In the context of other recent assessments of plant taxa, this puts *Aloe* in the Horn of Africa at higher risk than the global average for plants of (21%; Brummitt et al. 2015), cacti (31%) (Goettsch et al. 2015) and conifers (34%) (IUCN 2016b), but not as threatened as cycads (63%) (IUCN 2016b). The listing of nearly 10% of species in the Data Deficient category means that there is uncertainty about the best estimate of percentage of species that are threatened. The upper estimate of percentage threatened, where all DD species are assumed to be in threatened categories, is that as many as 45% of the *Aloe* are threatened (Table 1). If all DD species are assumed not to be threatened (lower estimate), the proportion threatened is still high, at 35%. Most of the species classed as threatened (96%) were classified according to criterion B1 (restricted extent of occurrence) or a combination of B1 and B2 (restricted area of occupancy), with just two species listed strictly based on AOO and one species listed under criterion D (small population size). For full listings of Red List assessments per species, see Table A2 in the supplementary material.

Threats to *Aloe* in the Horn of Africa

The principal threats to *Aloe* species are the expansion and intensification of crop farming and livestock farming (Figure 5). Major threats are also posed by the gathering of plants, and unintentional effects of logging and wood harvesting. All species categorised as Critically Endangered are affected by at least one of these threatening processes. Livestock farming is the most frequently listed threat for threatened species. The gathering of plants is predominantly a threat when the species is the target (i.e. harvesting *Aloe* species directly from the wild). The unintentional effects of logging and wood harvesting are when there has been cutting and charcoal burning and disturbance to the habitat which has caused degradation and mortality to *Aloe* populations. Other threats include the ongoing expansion of urban areas and the direct and indirect effects of fire, as well as climate-related processes such as drought.

Coincidence of Protected areas and Horn of Africa *Aloe* distributions

Protected areas in the countries where Horn of Africa *Aloe* species occur were first established in 1905 and have grown steadily until the present day, aside from the early 1970s when there was a spike in growth of PA coverage (Figure 6a). However, the recent growth in PAs has occurred in areas that do not overlap with *Aloe* distributions, and this pattern is especially apparent for threatened species: no additional threatened species have been included in PA coverage since the mid-1970s (Figure 6b). A similar pattern is shown when considering the proportion of *Aloe* species ranges receiving protection (Figure 7). Most species ranges are not covered by any PA and the proportion of species receiving >1% of the range protected has changed little since the mid-1970s. Only ~5% of *Aloe* species have at least half of their ranges protected under the current PA network.

Options to extend the PA network to cover all *Aloe* species

The *Aloe* distributions were buffered and merged to produce 528 unique patches (shown as dots on Figure 8), of which 50 are already completely within the PA network. The best scenario of the greedy algorithm – the one that required protection of the smallest total area – required 45 patches to be added to the PA network, these new patches totalling 824 km² (Table A6a in supplementary data). The first ten patches are illustrated in Figure 8a. Running the same algorithm on the combined threatened and Data Deficient species required protection of 25 additional patches totalling 542 km² (Table A6b); the first ten of these patches are shown in Figure 8b. In both analyses, the highest priority patch is the western limit of the Al Madow (Cal Madow) mountain range in Somalia, approximately 15 km north-west of Ceerigaabo (Erigavo), the capital city of the Sanaag region. In the best (i.e. least-area) scenario for protecting threatened *Aloe* species, half of the top ten patches were in Somalia. According to the WDPA dataset, there are 21 designated Wildlife Reserves and National Parks listed for Somalia. However, although the locations of these PAs were listed, the area was not reported, so buffers were not generated for any PA sites in Somalia. It is therefore possible that the ranges of some *Aloe* species overlap with the listed reserves and parks, but until a spatial boundary or estimate of area is added to this data, it is not possible to include these sites in the analysis

The distribution of protected areas varies considerably across the Horn of Africa countries, with only Ethiopia meeting Aichi Target 11 with 17% protected, although South Sudan is approaching this level with 15% of land area protected (Table A7 in supplementary data).

Representation of Horn of Africa *Aloe* in seed banks and botanic gardens

Aloe species in the Horn of Africa are represented in multiple botanic gardens around the world (see Table A8 in supplementary material). Botanic Gardens hold at least one collection for 69 of the 88 species (78%), leaving 19 species (22%) without any representation in any botanic garden. Some species are particularly well represented, such as *Aloe jucunda* with 78 collections. Threat status does not appear to be a factor in choice of *Aloe* species for ex situ collection (Figure 9). Only 14 of the *Aloe* species have been collected for ex situ storage as part of the Millennium Seed Bank partnership (see Table A8 in supplementary material). These 14 seed banked species represent 19% of the threatened species and 16% of non-threatened species (Table A9).

Discussion

Threats and extinction risk of *Aloe* in the Horn of Africa

Even though all *Aloe* in the Horn of Africa have now been assessed and published on the IUCN Red List, our estimate of 39% threatened is uncertain because 10% of species were listed as Data Deficient (DD). The DD categorisation may inadvertently deprioritise species from much needed conservation attention as DD species are more likely to be threatened (Bland et al. 2015). To address this data gap, techniques have been developed based on machine learning that utilise life-history, threat and environmental data to predict threat status of Not Evaluated or Data Deficient species (Bland and Böhm 2016; Darrah et al. 2017). Reduction in Data Deficiency can also be achieved through additional botanical surveys, although this is dependent on resources and accessibility to under-explored sites.

We demonstrate that occurrence data, primarily derived from herbarium specimens, can be successfully utilised to generate Red List assessments. However, inherent bias in herbarium specimen collections can influence geographic range estimates such as EOO and AOO. The use of occurrence data and a 2 × 2 km reference scale to calculate AOO was deemed appropriate here because *Aloe* in this region often have fragmented and dispersed distributions and therefore low AOO values are likely to be accurate. Furthermore, *Aloe* species are relatively conspicuous and have been targeted for botanical collection in this region, thereby reducing potential bias from under-sampling, although some areas remain unexplored. To reduce the error of mis-classifying species as threatened when they were simply under-represented by occurrence records, we utilised expert opinion derived from extensive fieldwork in the region, as well as knowledge of habitat preferences and elevation ranges. Incorporating expert opinion to estimate geographic ranges is susceptible to subjective bias if not elicited in a structured way (McBride et al. 2012), but is useful in reducing omission error rates from occurrence data (Rondinini et al. 2006) and can be used to document uncertainty in Red List assessments (IUCN Standards And Petitions Subcommittee 2014).

Coincidence of Protected areas and Horn of Africa *Aloe* distributions

In contrast to our geographic range estimates for Red List assessment, we did not utilise expert opinion when investigating overlap of *Aloe* ranges with the protected area network. This is partly because the expert ranges were not mapped, but also because these ranges may introduce commission errors (Rondinini et al. 2006), which in the context of protected areas could mean declaring a species as being protected when in fact there is no population within a protected area.

The pattern of steady growth in protected areas across the study region is consistent with global patterns (Butchart et al. 2012) and this is reflected in increasing levels of protection for *Aloe* species. However, the placement of protected areas established since the 1970s has added limited additional protection to *Aloe* species, both in terms of numbers of species protected and the proportions of ranges protected (Figures 6 & 7). This pattern is also reflected at the global scale when multiple biodiversity targets are considered (Butchart et al. 2012, 2015). The size of the buffer around *Aloe* point distributions, used to determine geographic ranges, did not change this overall pattern, but the number of species protected did increase by 32% when comparing 2km to 20 km buffers for the current PA network. Di Marco et al. (2017) recommend using resolutions of 20 – 30 km, although this applies to the use of range maps rather than buffered point maps. For point occurrence records, the use of 2 km buffers is likely to produce a conservative estimate of range size, minimising commission errors.

Options to extend the PA network to cover all *Aloe* species

The greedy algorithm has been shown to perform well when applied to target-setting scenarios such as finding the highest number of species in the smallest area (Joppa et al. 2013). However, it may not always find the optimal solution because the 'greedy' path may miss a patch with a large number of unprotected species. An alternative and commonly applied approach to conservation problems is Marxan (Ball et al. 2009), which adopts a simulated annealing technique. Marxan usually requires more detailed data on planning unit costs, which were not available here. The results of the greedy analysis represent a set of priority patches defined simply by species and area. An extension of this work could be to obtain data on planning costs, opportunities and difficulty in establishing new protected areas, and in this scenario a more comprehensive conservation planning tool like Marxan would be appropriate.

A major area of uncertainty in this analysis is the extent of protected area coverage in Somalia. Data on PAs in Somalia have recently been added to the WDPA dataset, but because only point data were provided, without reported area or year of establishment, they did not meet the requirements for inclusion in the analysis. Several patches from Somalia were identified as priorities for *Aloe* protection. The current lack of PA coverage for Somalia suggests it is not likely to meet its target for 17% coverage by 2020. However, if Somalia were to officially designate and provide spatial boundaries for the sites already submitted to WDPA, it would be an important step towards the target and would allow the kind of gap analysis illustrated here. Political instability in Somalia has hampered the safeguarding of biodiversity through protected areas, although the need to improve management and enforcement are recognised in the most recent National Biodiversity Strategy and Action Plan (Ullah and Gadain 2016). In contrast, Ethiopia and South Sudan have grown protected areas steadily and may be more likely to establish new PAs even though South Sudan is close to meeting (15.5%), and Ethiopia has already met (17.62%), the target of 17% coverage by 2020.

Another shortcoming of the greedy algorithm is that is does not consider resilience or redundancy in the PA network, rather is just looks for representation – i.e. all species protected in at least one patch. Representation may not be adequate for the long-term persistence of a species (Santini et al. 2014), but until more detailed data become available on distribution, dispersal ability and minimum viable population size for *Aloes*, representation remains the minimal target.

Representation of Horn of Africa *Aloe* in seed banks and botanic gardens

Aloe species from the Horn of Africa are quite well represented in botanic gardens as live specimens, but not so well represented in ex situ seed bank collections. A recent review of ex situ collections in seed banks and botanic gardens suggests that although threatened species have been targets for collection, the species held in seed banks are more likely to be non-threatened (66%) than threatened (34%) (O'Donnell and Sharrock 2017). Our results show a slight preference for seed banking threatened *Aloe* species, but there are still considerable gaps, with 25 threatened species lacking a seed bank collection.

Conclusions

The results presented here represent the new state of the art for assessment of conservation status of *Aloe* species in the Horn of Africa, thereby filling an important knowledge gap. Our results indicate that extinction risk is high, and protected area coverage is currently inadequate to represent all *Aloe* species, although this could be achieved with a relatively modest increase in protected area coverage using an optimisation approach. Similarly, analysis of ex situ conservation reveals gaps in species coverage, which we highlight as priorities to be addressed.

The data generated here on *Aloe* distributions and extinction risk assessments can also contribute to multi-taxon conservation prioritisation schemes, site-prioritisation schemes such as Important Plant Areas and Areas of Zero extinction, and can support country-level biodiversity action plans and strategies. Ongoing monitoring and survey of populations will be an essential task to ensure re-assessment of conservation status is robust and to determine whether conservation gaps are being addressed.

Supplementary Material

Table A1. Additional species names excluded from the study

Table A2. Assessment ratings

Table A3. IUCN Red List Criteria summary

Table A4. IUCN Threat classification scheme

Table A5. Testing iterations needed for greedy algorithm

Table A6. Final sequence of patches for all species and threatened species

Table A7. Protected areas per country

Table A8. *Aloe* species in botanic garden collections

References

Arponen A (2012) Prioritizing species for conservation planning. Biodivers Conserv 21:875–893. doi: 10.1007/s10531-012-0242-1

Bachman SP, Moat J, Hill A, et al (2011) Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. Zookeys 150:117. doi: 10.3897/zookeys.150.2109

Ball IR, Possingham HP, Watts ME (2009) Marxan and Relatives: Software for Spatial Conservation Prioritization

Bjorå CS, Wabuyele E, Grace OM, et al (2015) The uses of Kenyan aloes: an analysis of implications for names, distribution and conservation. J Ethnobiol Ethnomed 11:82. doi: 10.1186/s13002-015-0060-0

Bland LM, Böhm M (2016) Overcoming data deficiency in reptiles. Biol Conserv. doi: 10.1016/j.biocon.2016.05.018

Bland LM, Collen B, Orme CDL, Bielby J (2015) Predicting the conservation status of data-deficient species. Conserv Biol 29:250–259. doi: 10.1111/cobi.12372

Brooks TM, Mittermeier RA, Da Fonseca GAB, et al (2006) Global biodiversity conservation priorities. Science (80-.). 313:58–61

Brummitt NA, Bachman SP, Griffiths-Lee J, et al (2015) Green Plants in the Red: A Baseline Global Assessment for the IUCN Sampled Red List Index for Plants. PLoS One 10:e0135152. doi: 10.1371/journal.pone.0135152

Butchart SHM, Clarke M, Smith RJ, et al (2015) Shortfalls and Solutions for Meeting National and Global Conservation Area Targets. Conserv Lett 8:329–337. doi: 10.1111/conl.12158

Butchart SHM, Scharlemann JPW, Evans MI, et al (2012) Protecting important sites for biodiversity contributes to meeting global conservation targets. PLoS One 7:32529. doi: 10.1371/journal.pone.0032529

Cardinale BJ, Duffy JE, Gonzalez A, et al (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67

Cardoso P, Erwin TL, Borges PAV, New TR (2011) The seven impediments in invertebrate conservation and how to overcome them. Biol Conserv 144:2647–2655. doi: 10.1016/j.biocon.2011.07.024

CBD (2010) X/17. Consolidated update of the Global Strategy for Plant Conservation 2011-2020

Ceballos G, Ehrlich PR, Barnosky AD, et al (2015) Accelerated modern human – induced species losses: entering the sixth mass extinction. Sci Adv 1:1–5. doi: 10.1126/sciadv.1400253

CITES-Secretariat (2016) CITES - Convention on International Trade in Endangered Species of Wild Fauna and Flora. https://cites.org/. Accessed 26 Jan 2016

Collen B, Ram M, Zamin T, Mcrae L (2008) The tropical biodiversity data gap: addressing disparity in global monitoring. Mongabay.com Open Access J -Tropical Conserv Sci

Open Access J -Tropical Conserv Sci 11:75–8875

Dahlberg A, Mueller GM (2011) Applying IUCN red-listing criteria for assessing and reporting on the conservation status of fungal species. Fungal Ecol 4:147–162. doi: 10.1016/j.funeco.2010.11.001

Darbyshire I, Anderson S, Asatryan A, et al (2017) Important Plant Areas: revised selection criteria for a global approach to plant conservation. Biodivers Conserv 1–34. doi: 10.1007/s10531-017-1336-6

Darkoh MBK (2003) Regional perspectives on agriculture and biodiversity in the drylands of Africa. J Arid Environ 54:261–279. doi: 10.1006/jare.2002.1089

Darrah SE, Bland LM, Bachman SP, et al (2017) Using coarse-scale species distribution data to predict extinction risk in plants. Divers Distrib 23:435–447. doi: 10.1111/ddi.12532

Demissew S, Nordal I (2010) Aloes and other lilies of Ethiopia and Eritrea. Shama Books

Di Marco M, Watson JEM, Possingham HP, Venter O (2017) Limitations and trade-offs in the use of species distribution maps for protected area planning. J Appl Ecol 54:402–411. doi: 10.1111/1365-2664.12771

ESRI (2017) ArcGIS Pro

Ethiopian Biodiveristy Institue (2015) Ethiopia's National Biodiversity Strategy and Action Plan

Gaston KJ, Rodrigues ASL (2003) Reserve Selection in Regions with Poor Biological Data. Conserv Biol 17:188–195. doi: 10.1046/j.1523-1739.2003.01268.x

Goettsch B, Hilton-Taylor C, Cruz-Piñón G, et al (2015) High proportion of cactus species threatened with extinction. Nat Plants 1:. doi: 10.1038/nplants.2015.142

Grace OM (2011) Current perspectives on the economic botany of the genus Aloe L. (Xanthorrhoeaceae). South African J Bot 77:980–987. doi: 10.1016/j.sajb.2011.07.002

Grand J, Cummings MP, Rebelo TG, et al (2007) Biased data reduce efficiency and effectiveness of conservation reserve networks. Ecol Lett 10:364–374. doi: 10.1111/j.1461-0248.2007.01025.x

Grantham HS, Wilson KA, Moilanen A, et al (2009) Delaying conservation actions for improved knowledge: how long should we wait? Ecol Lett 12:293–301. doi: 10.1111/j.1461-0248.2009.01287.x

Hoffmann M, Brooks T, da Fonseca G, et al (2008) Conservation planning and the IUCN Red List. Endanger Species Res 6:113–125. doi: 10.3354/esr00087

Hooper DU, Adair EC, Cardinale BJ, et al (2012) A global synthesis reveals biodiversity loss as a major driver of ecosystem change. Nature 486:105–108. doi: 10.1038/nature11118

IUCN (2016a) A global standard for the Identification of Key Biodiversity Areas, version 1.0. 1st Edition.

IUCN (2012) IUCN Red List Categories and Criteria: Version 3.1. Second edition. IUCN, Gland, Switzerland and Cambridge, UK

IUCN (2018) Table 1: Numbers of threatened species by major groups of organisms (1996–2018). http://cmsdocs.s3.amazonaws.com/summarystats/2018-2_Summary_Stats_Page_Documents/2018_2_RL_Stats_Table_1.pdf

IUCN (2016b) Table 1: Numbers of threatened species by major groups of organisms (1996–2016). http://cmsdocs.s3.amazonaws.com/summarystats/2017-1_Summary_Stats_Page_Documents/2017_1_RL_Stats_Table_1.pdf

IUCN Standards And Petitions Subcommittee (2014) Guidelines for using the IUCN Red List Categories and Criteria. Version 11 (February 2014). Prep. by Stand. Petitions Work. Gr. IUCN SSC Biodivers. Assessments Subcomm. August 2008 1:86

Joppa LN, Butchart SHM, Hoffmann M, et al (2016) Impact of alternative metrics on estimates of extent of occurrence for extinction risk assessment. Conserv Biol 30:362–370. doi: 10.1111/cobi.12591

Joppa LN, Visconti P, Jenkins CN, Pimm SL (2013) Achieving the convention on biological diversity's goals for plant conservation. Science 341:1100–3. doi: 10.1126/science.1241706

Kehoe L, Romero-Muñoz A, Polaina E, et al (2017) Biodiversity at risk under future cropland expansion and intensification. Nat Ecol Evol. doi: 10.1038/s41559-017-0234-3

Klopper RR, Smith G, Crouch N, et al (2013) Aloes of the World Project: background and progress. In: XIXth AETFAT Congress, 26–30 April 2010, At Antananarivo, Madagascar. pp 332–336

Le Bras G, Pignal M, Jeanson ML, et al (2017) The French Muséum national d'histoire naturelle vascular plant herbarium collection dataset. Sci Data 4:170016. doi: 10.1038/sdata.2017.16

Li J, Gale SW, Kumar P, et al (2018) Prioritizing the orchids of a biodiversity hotspot for conservation based on phylogenetic history and extinction risk. Bot J Linn Soc 186:473–497. doi: 10.1093/botlinnean/box084

Lillesø JB, van Breugel P, Kindt R, et al (2011) Potential Natural Vegetation of Eastern Africa (Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda and Zambia), Volume 1: University of Copenhagen, University of Copenhagen

McBride MF, Garnett ST, Szabo JK, et al (2012) Structured elicitation of expert judgments for threatened species assessment: a case study on a continental scale using email. Methods Ecol Evol 3:906–920. doi: 10.1111/j.2041-210X.2012.00221.x

McCarthy DP, Donald PF, Scharlemann JPW, et al (2012) Financial Costs of Meeting Global Current Spending and Unmet Needs. Science 338:946–949

Meyer C, Kreft H, Guralnick R, Jetz W (2015) Global priorities for an effective information basis of biodiversity distributions. Nat Commun 6:8221. doi: 10.1038/ncomms9221

Meyer C, Weigelt P, Kreft H (2016) Multidimensional biases, gaps and uncertainties in global plant occurrence information. Ecol Lett. doi: 10.1111/ele.12624

Mittermeier RAA, Gil PR, Hoffman M, et al (2004) Hotspots Revisited : Earth's biologically richest and most endangered ecoregions. CEMEX and Agrupación Sierra Madre, Mexico City, Mexico City

Moat J (2007) Conservation assessment tools extension for ArcView 3. x, version 1.2. GIS Unit, R Bot Gard Kew

Myers N, Mittermeier RA, Mittermeier CG, et al (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–8. doi: 10.1038/35002501

Newbold T, Tittensor DP, Harfoot MBJ, et al (2018) Non-linear changes in modelled terrestrial ecosystems subjected to perturbations. doi: 10.1101/439059

O'Donnell K, Sharrock S (2017) The contribution of botanic gardens to ex situ conservation through seed banking. Plant Divers 39:373–378. doi: 10.1016/J.PLD.2017.11.005

R Core Team (2016) R: A language and environment for statistical computing

Raimondo D, Von Statden L, Foden W, et al (2009) Red List of South African Plants. Strelitzia 25:668 ST-Red List of South African Plants

Rakotoarinivo M, Dransfield J, Bachman SP, et al (2014) Comprehensive red list assessment reveals exceptionally high extinction risk to Madagascar palms. PLoS One 9:. doi: 10.1371/journal.pone.0103684

Rakotoarisoa SE, Klopper RR, Smith GF (2014) A preliminary assessment of the conservation status of the genus Aloe L. In Madagascar. Bradleya 32:81–91

Ricketts TH, Dinerstein E, Boucher T, et al (2005) Pinpointing and preventing imminent extinctions. PNAS 102:18497–18501. doi: www.pnas.org_cgi_doi_10.1073_pnas.0509060102

Rivers MC (2017) The Global Tree Assessment - Red Listing the world's trees. BGJournal 14:16–19

Rivers MC, Taylor L, Brummitt NA, et al (2011) How many herbarium specimens are needed to detect threatened species? Biol Conserv 144:2541–2547. doi: 10.1016/j.biocon.2011.07.014

Rondinini C, Wilson KA, Boitani L, et al (2006) Tradeoffs of different types of species occurrence data for use in systematic conservation planning. Ecol Lett 9:1136–1145. doi: 10.1111/j.1461-0248.2006.00970.x

Salafsky N, Salzer D, Stattersfield AJ, et al (2008) A standard lexicon for biodiversity conservation: unified classifications of threats and actions. Conserv Biol 22:897–911. doi: https://doi.org/10.1111/j.1523-1739.2008.00937.x

Santini L, Di Marco M, Boitani L, et al (2014) Incorporating spatial population structure in gap analysis reveals inequitable assessments of species protection. Divers Distrib 20:698–707. doi: 10.1111/ddi.12198

Stuart SN, Wilson EO, McNeely JA, et al (2010) Ecology. The barometer of life. Science 328:177

Thiers BM (2015) Index Herbariorum: A global directory of public herbaria and associated staff. In: New York Bot. Gard. Virtual Herb.

Tierney M, Almond R, Stanwell-Smith D, et al (2014) Use it or lose it: measuring trends in wild species subject to substantial use. ORYX 48:420–429. doi: 10.1017/S0030605313000653

Ullah S, Gadain H (2016) National Biodiversity Strategy and Action Plan (NBSAP) of Somalia

UNEP-WCMC and IUCN (2018) The World Database on Protected Areas (WDPA) [On-line]. In: Cambridge, UK

UNEP/CBD (2010) The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. In: UNEP/CBD/COP/DEC/X/2. https://www.cbd.int/decision/cop/?id=12268

Urban MC (2015) Accelerating extinction risk from climate change. Science (80-) 348:571–573. doi: 10.1126/science.aaa4984

Venter O, Fuller RA, Segan DB, et al (2014) Targeting Global Protected Area Expansion for Imperiled Biodiversity. PLoS Biol 12:1001891. doi: 10.1371/journal.pbio.1001891

Venter O, Sanderson EW, Magrach A, et al (2016) Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nat Commun 7:12558. doi: 10.1038/ncomms12558

Waldron A, Mooers AO, Miller DC, et al (2013) Targeting global conservation funding to limit immediate biodiversity declines. doi: 10.5061/dryad.p69t1

Wilkin P, Suksathan P, Keeratikiat K, et al (2013) A new species from Thailand and Burma, Dracaena kaweesakii Wilkin & Suksathan (Asparagaceae subfamily Nolinoideae). PhytoKeys 101–12. doi: 10.3897/phytokeys.26.5335

Figure captions

Figure 1.

Native distribution of the genus *Aloe* according to the World Checklist of Selected Plant Families (WCSP) using the Taxonomic Database Working Group geopolitical regions at level 3 (WCSP 2013). Richness of *Aloe* species is shown in conjunction with the 'biodiversity hotspots' (red hatched lines) sensu Mittermeier et al. (2004)

Figure 2.

A - Study area from which all *Aloe* species were selected for inclusion in the analysis. Each species had to occur in the study area (red boundary), but occurrence data for some species spread outside the study area (B).

Figure 3.

Distribution of species according to number of occurrence records (Number of occurrence records = 711, number of species = 88, mean occurrence records per species (solid black vertical line) = 8.07).

Figure 4.

Diagram to illustrate the greedy algorithm used to estimate the additional protected areas required to mean that all species of Aloe in the region are protected in at least part of their distribution. The patch with the highest number of species is selected first, in this example patch 2, which contains 4 species: A, C, D and E. The next patch is selected based on the highest number of species that have not already been included in patch 2, which is patch 4, containing species E, F and G. Only 2 new species are added because species E was already included in patch 2. The algorithm then needs to decide on the final patch from a choice of patch 1 or patch 3. Both patches have an equal number of one new species to add (species B), so a random selection is made.

Figure 5.

Importance of different threatening processes affecting Aloe species. Number of species affected by each threat are broken down by IUCN Red List category. Threat classification follows IUCN Red List threat classification scheme Version 3.2 with some modifications to labels. The IUCN threat codes for each labels are: Livestock farming = 2.3, 2.3.1, 2.3.2; Expansion/intensification of crop farming = 2.1.1, 2.1.2, 2.1.3, 2.1.4; Logging & wood harvesting = 5.3, 5.3.1, 5.3.2, 5.3.3, 5.3.4; Gathering terrestrial plants = 5.2, 5.2.1, 5.2.3; Fire & fire suppression = 7.1, 7.3, 7.1.1, 7.1.3; Droughts = 11.2; Wood & pulp plantations = 2.2, 2.2.1; Housing & urban areas = 1.1

Figure 6.

Growth in PA coverage over time, across the countries where Horn of Africa *Aloe* occur (a) compared with number of *Aloe* species' ranges that overlap protected areas (b). *Aloe* species ranges were derived from occurrence points buffered at 2, 5, 10 and 20km radius for all species (solid lines) and threatened species (dashed lines).

Figure 7.

Mean proportion of *Aloe* species ranges (based on 2 km buffer of points) that overlap with PAs from 1932 – 2017. For example, in 2017, ~5% of all Aloe species had at least 50% of the range covered by a PA.

Figure 8.

Maps illustrating the location of the top 10 sites in order of priority to capture all species (a), and all threatened species (b), with the minimum amount of additional PA. All sites are shown as red patches and the existing PA network is shown with green polygons. A full list of sites is provided in Table A6 supplementary material.

Figure 9.

Number of collections of *Aloe* in botanic gardens grouped by threat status: threatened, not threatened and Data Deficient.

Figure 10.

Number of banked collections of *Aloe* in the Millennium Seed Bank grouped by threatened (6) and not threatened (8) species. Non-banked species were grouped by threatened (25), not threatened (40), and data deficient (9) species.

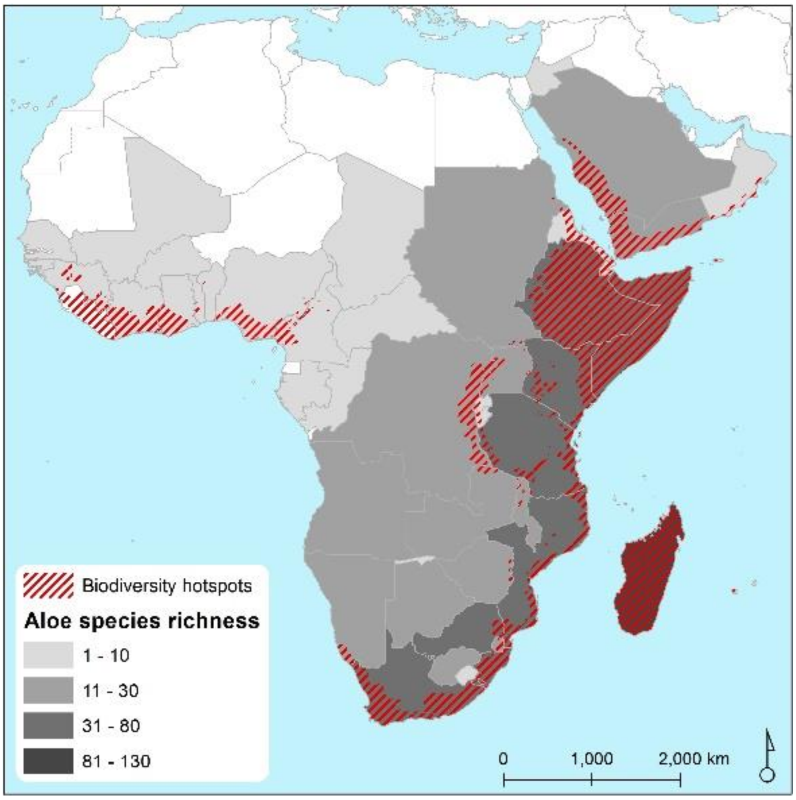


Figure 1.

Native distribution of the genus *Aloe* according to the World Checklist of Selected Plant Families (WCSP) using the Taxonomic Database Working Group geopolitical regions at level 3 (WCSP 2013). Richness of *Aloe* species is shown in conjunction with the 'biodiversity hotspots' (red hatched lines) sensu Mittermeier et al. (2004)

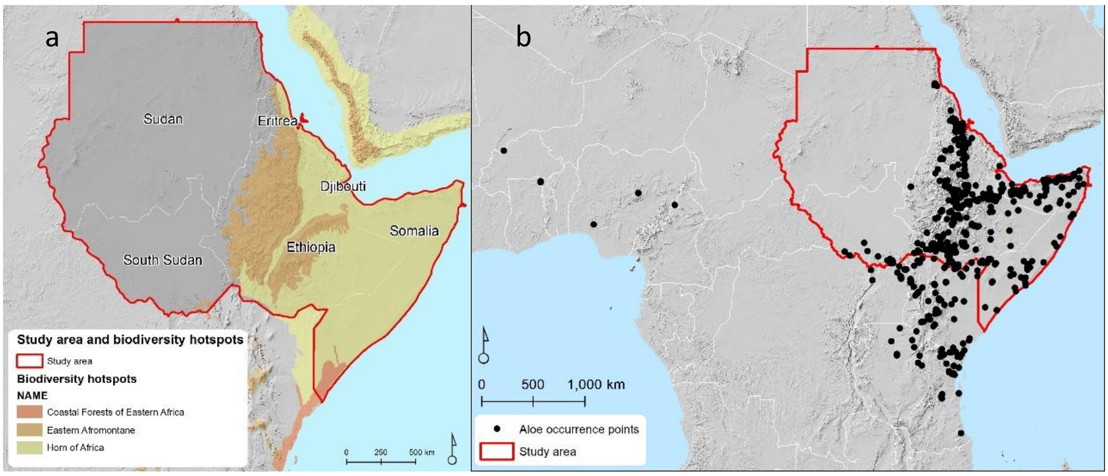


Figure 2.

Study area from which all *Aloe* species were selected for inclusion in the analysis (a). Each species had to occur in the study area (red boundary), but occurrence data for some species spread outside the study area (b).

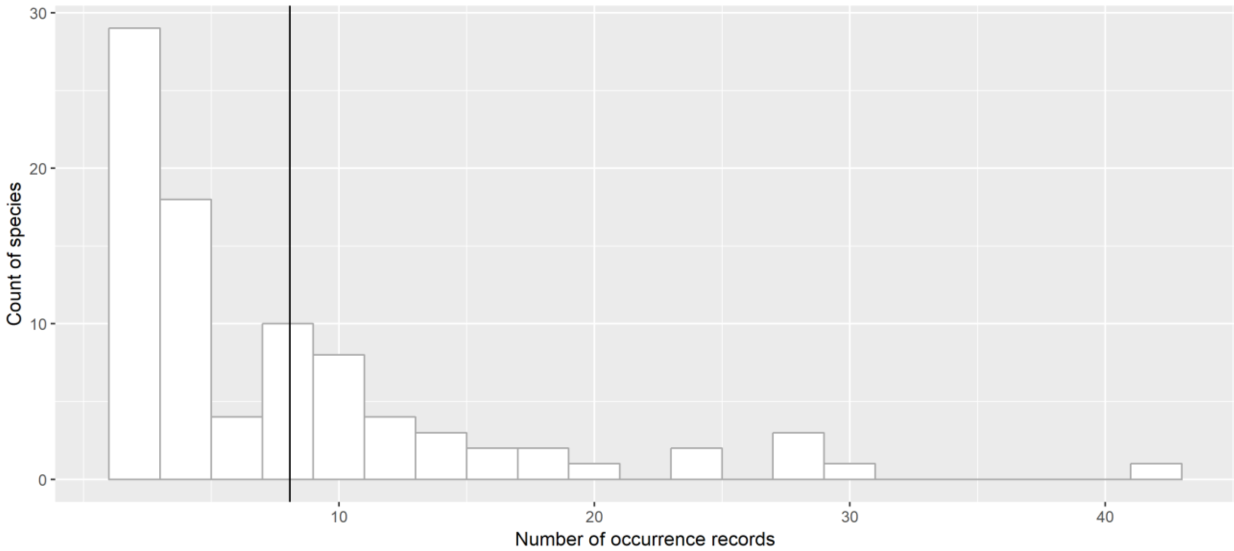


Figure 3.

Distribution of species according to number of occurrence records (Number of occurrence records = 711, number of species = 88, mean occurrence records per species (solid black vertical line) = 8.07).

Patch	Species
1	A, B, C
2	A, C, D, E
3	B
4	E, F, G

Algorithm step	Number of Protected species
1	4 (A, C, D, E)
2	2 (F, G)
3	1 (B)

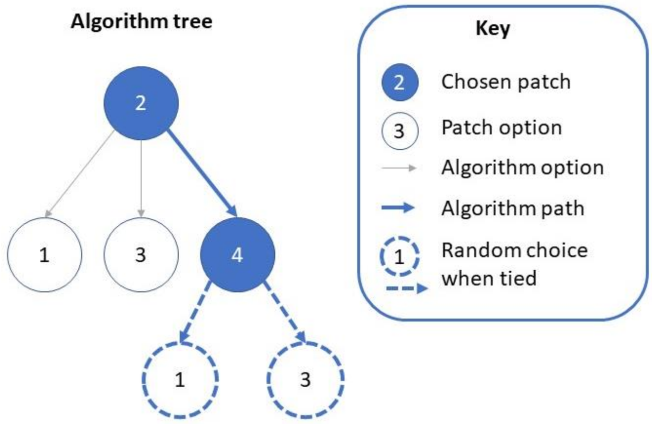


Figure 4.

Diagram to illustrate the greedy algorithm used to estimate the additional protected areas required to mean that all species of Aloe in the region are protected in at least part of their distribution. The patch with the highest number of species is selected first, in this example patch 2, which contains 4 species: A, C, D and E. The next patch is selected based on the highest number of species that have not already been included in patch 2, which is patch 4, containing species E, F and G. Only 2 new species are added because species E was already included in patch 2. The algorithm then needs to decide on the final patch from a choice of patch 1 or patch 3. Both patches have an equal number of one new species to add (species B), so a random selection is made.

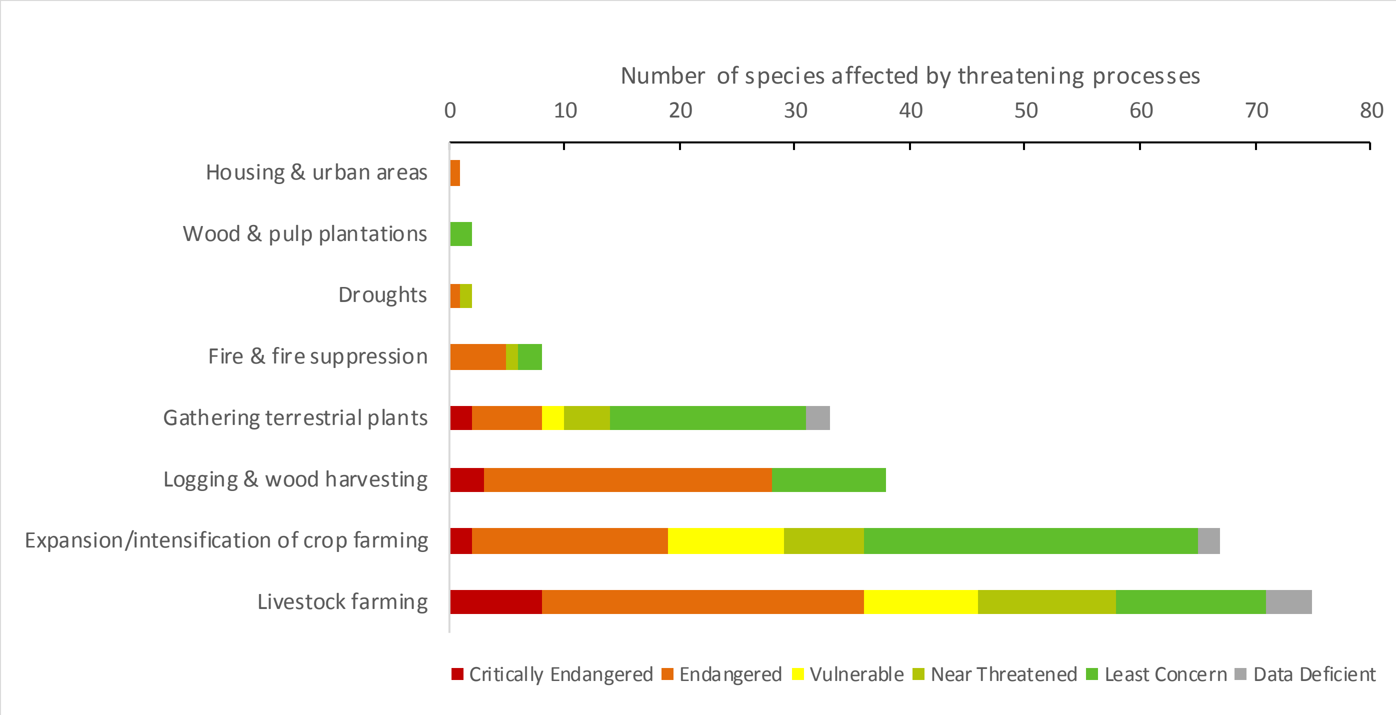


Figure 5.

Importance of different threatening processes affecting Aloe species. Number of species affected by each threat are broken down by IUCN Red List category. Threat classification follows IUCN Red List threat classification scheme Version 3.2 (Table A4 in the supplementary data) with some modifications to labels. The IUCN threat codes for each labels are: Livestock farming = 2.3, 2.3.1, 2.3.2; Expansion/intensification of crop farming = 2.1.1, 2.1.2, 2.1.3, 2.1.4; Logging & wood harvesting = 5.3, 5.3.1, 5.3.2, 5.3.3, 5.3.4; Gathering terrestrial plants = 5.2, 5.2.1, 5.2.3; Fire & fire suppression = 7.1, 7.3, 7.1.1, 7.1.3; Droughts = 11.2; Wood & pulp plantations = 2.2, 2.2.1; Housing & urban areas = 1.1

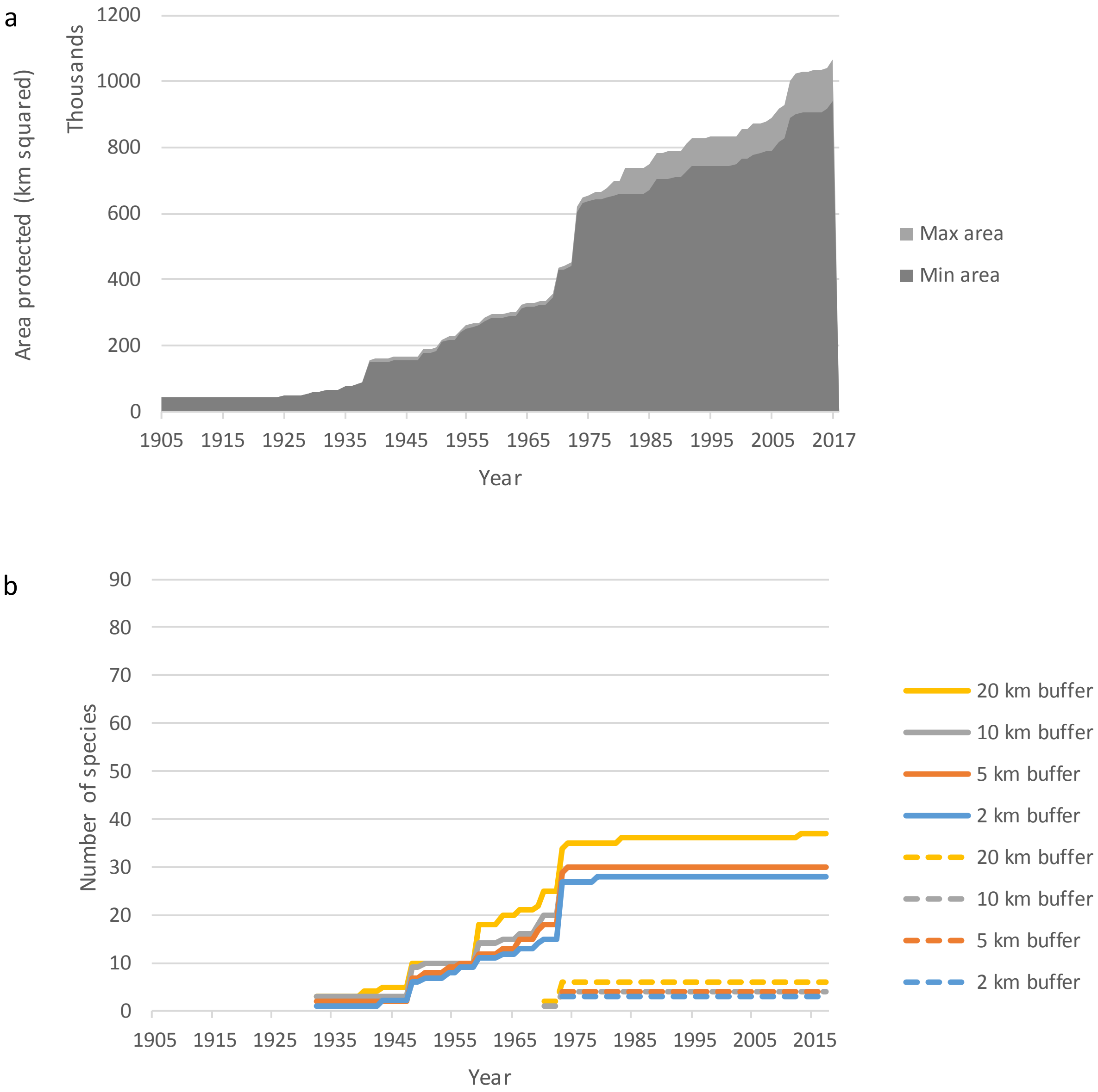


Figure 6.

Growth in PA coverage over time, across the countries where Horn of Africa *Aloe* occur (a) compared with number of *Aloe* species' ranges that overlap protected areas (b). *Aloe* species ranges were derived from occurrence points buffered at 2, 5, 10 and 20km radius for all species (solid lines) and threatened species (dashed lines). In (a) the minimum (min) protected area (PA) coverage was calculated from all polygons in the PA dataset and the maximum (max) PA coverage was calculated by adding all polygons plus the buffered point layer for PAs that did not have spatial boundaries defined.

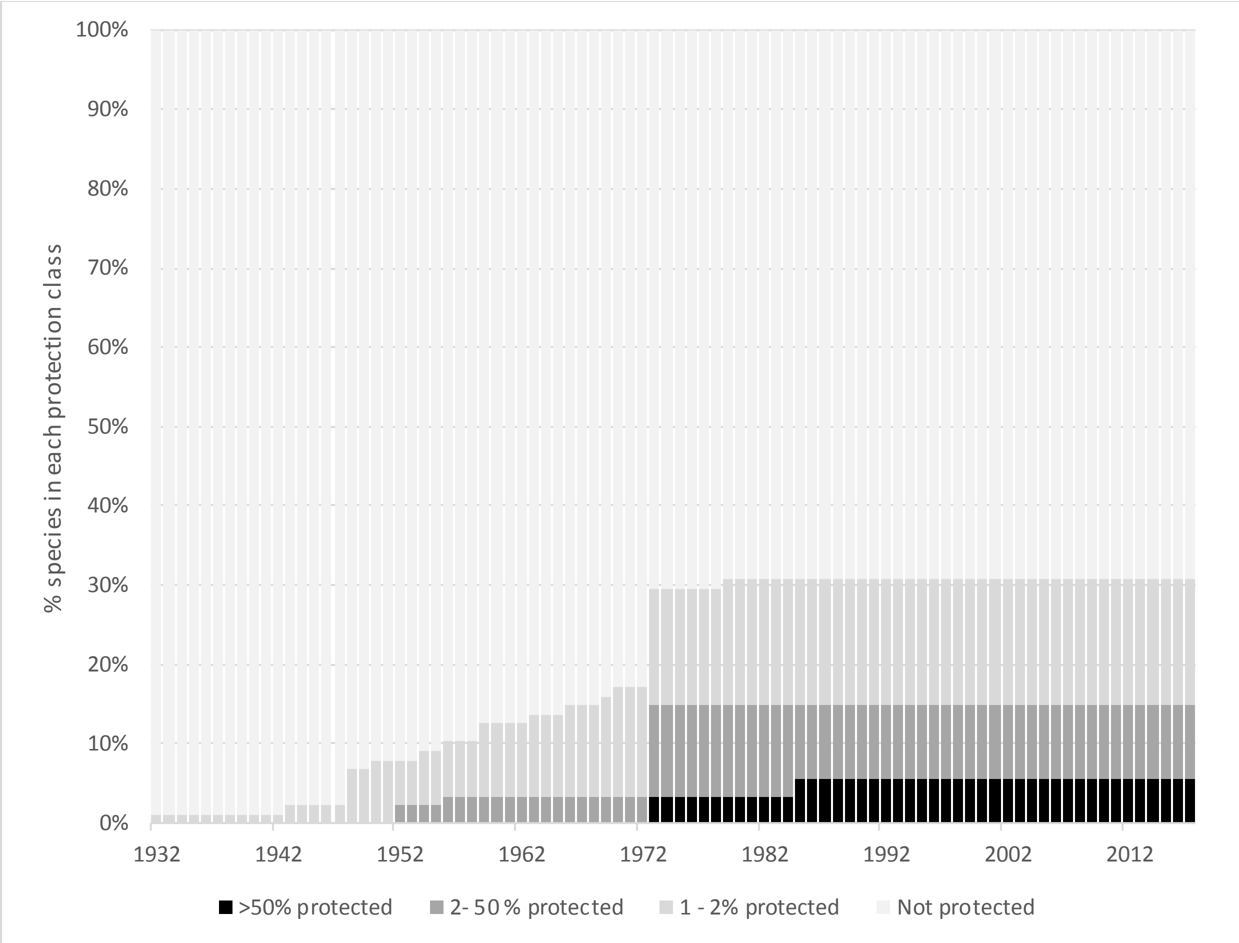


Figure 7.

Mean proportion of *Aloe* species ranges (based on 2 km buffer of points) that overlap with PAs from 1932 – 2017. For example, in 2017, ~5% of all Aloe species had at least 50% of the range covered by a PA.

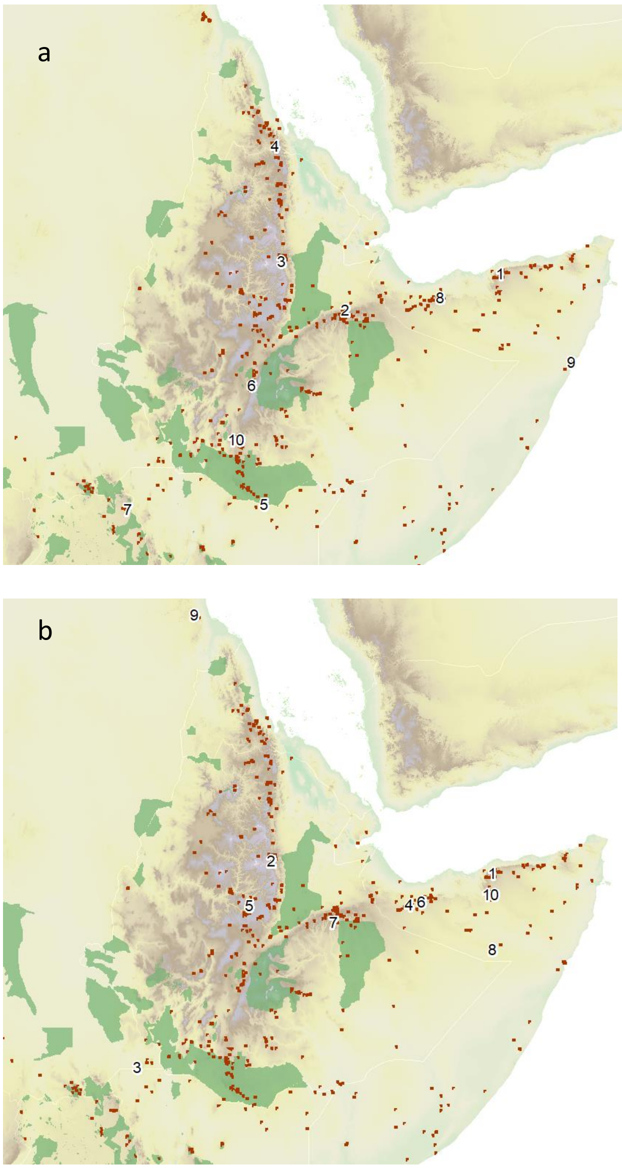


Figure 8.

Maps illustrating the location of the top 10 sites in order of priority to capture all species (a), and all threatened species (b), with the minimum amount of additional PA. All sites are shown as red patches and the existing PA network is shown with green polygons. A full list of sites is provided in Table A6 supplementary material.

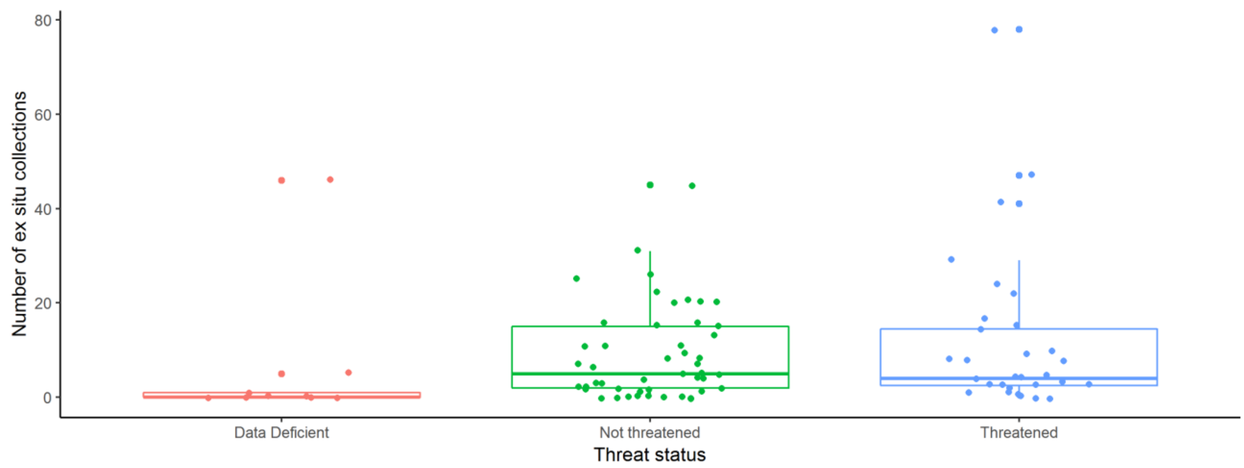


Figure 9.

Number of collections of *Aloe* in botanic gardens grouped by threat status: Threatened, Not Threatened and Data Deficient. There was no significant difference between in number of ex situ collections for 'Threatened' and 'Not Threatened' species t = -0.85, df = 43.06, p-value = 0.3987.

Category	Count of species	Percentage	Method
Critically Endangered (CR)	4	5%	Sum of CR
Endangered (EN)	22	25%	Sum of EN
Vulnerable (VU)	5	6%	Sum of VU
Lower estimate % threatened	-	35%	(CR + EN + VU)/ (Total assessed)
Best estimate % threatened	**-**	**39%**	**(CR + EN + VU) / (Total assessed - DD)**
Upper estimate % threatened	-	45%	(CR + EN + VU + DD) / (Total assessed)
Near Threatened (NT)	9	10%	Sum of NT
Least Concern (LC)	39	44%	Sum of LC
Data Deficient (DD)	9	10%	Sum of DD
Total assessed	88		CR +EN + VU + NT + LC + DD

Table 1.

Summary of final Red List assessment ratings for 88 assessed Aloes. The best estimate for the percentage of species threatened (accounting for DD species) is 39% (highlighted in the table) but could be as high as 45% if all species presently rated as DD were eventually assessed as threatened.

High extinction risk and conservation gaps for *Aloe* (Asphodelaceae) in the Horn of Africa

Supplementary Material

Table A1. Additional species names excluded from the study

Genus	Species	author	citation
Aloe	anodonta	T.A.McCoy & Lavranos	CactusWorld 33: 180 (2015)
Aloe	austrosudanica	T.A.McCoy	Avonia 34: 201 (2016)
Aloe	downsiana	T.A.McCoy & Lavranos	CactusWorld 25(3): 139 (2007)
Aloe	ithya	T.A.McCoy & L.E.Newton	Haseltonia 19: 64 (2014)
Aloe	lukeana	T.C.Cole	Cact. Succ. J. (Los Angeles) 87: 156 (2015)
Aloe	montis-nabro	Orlando & El Azzouni	CactusWorld 32: 201 (2014)
Aloe	nugalensis	Thulin	Nordic J. Bot. 30: 729 (2012).
Aloe	omoana	T.A.McCoy & Lavranos	Cact. World 25: 139 (2007).
Aloe	zubb	T.A.McCoy & Lavranos	CactusWorld 33: 31 (2015).

Table A2. Assessment ratings (See separate excel file)

https://github.com/stevenpbachman/thesis_extra/blob/master/A2_assessment_ratings.csv

Table A3. IUCN Red List Criteria summary (see separate pdf)

SUMMARY OF THE FIVE CRITERIA (A-E) USED TO EVALUATE IF A TAXON BELONGS IN AN IUCN RED LIST THREATENED CATEGORY (CRITICALLY ENDANGERED, ENDANGERED OR VULNERABLE).[1]

A. Population size reduction. Population reduction (measured over the longer of 10 years or 3 generations) based on any of A1 to A4

	Critically Endangered	Endangered	Vulnerable
A1	≥ 90%	≥ 70%	≥ 50%
A2, A3 & A4	≥ 80%	≥ 50%	≥ 30%

A1 Population reduction observed, estimated, inferred, or suspected in the past where the causes of the reduction are clearly reversible AND understood AND have ceased.

A2 Population reduction observed, estimated, inferred, or suspected in the past where the causes of reduction may not have ceased OR may not be understood OR may not be reversible.

A3 Population reduction projected, inferred or suspected to be met in the future (up to a maximum of 100 years) *[(a) cannot be used for A3]*.

A4 An observed, estimated, inferred, projected or suspected population reduction where the time period must include both the past and the future (up to a max. of 100 years in future), and where the causes of reduction may not have ceased OR may not be understood OR may not be reversible.

based on any of the following:

- **(a)** direct observation *[except A3]*
- **(b)** an index of abundance appropriate to the taxon
- **(c)** a decline in area of occupancy (AOO), extent of occurrence (EOO) and/or habitat quality
- **(d)** actual or potential levels of exploitation
- **(e)** effects of introduced taxa, hybridization, pathogens, pollutants, competitors or parasites.

B. Geographic range in the form of either B1 (extent of occurrence) AND/OR B2 (area of occupancy)

	Critically Endangered	Endangered	Vulnerable
B1. Extent of occurrence (EOO)	< 100 km²	< 5,000 km²	< 20,000 km²
B2. Area of occupancy (AOO)	< 10 km²	< 500 km²	< 2,000 km²
AND at least 2 of the following 3 conditions:			
(a) Severely fragmented **OR** Number of locations	= 1	≤ 5	≤ 10

(b) Continuing decline observed, estimated, inferred or projected in any of: **(i)** extent of occurrence; **(ii)** area of occupancy; **(iii)** area, extent and/or quality of habitat; **(iv)** number of locations or subpopulations; **(v)** number of mature individuals

(c) Extreme fluctuations in any of: **(i)** extent of occurrence; **(ii)** area of occupancy; **(iii)** number of locations or subpopulations; **(iv)** number of mature individuals

C. Small population size and decline

	Critically Endangered	Endangered	Vulnerable
Number of mature individuals	< 250	< 2,500	< 10,000
AND at least one of C1 or C2			
C1. An observed, estimated or projected continuing decline of at least (up to a max. of 100 years in future):	25% in 3 years or 1 generation (whichever is longer)	20% in 5 years or 2 generations (whichever is longer)	10% in 10 years or 3 generations (whichever is longer)
C2. An observed, estimated, projected or inferred continuing decline AND at least 1 of the following 3 conditions:			
(a) (i) Number of mature individuals in each subpopulation	≤ 50	≤ 250	≤ 1,000
(a) (ii) % of mature individuals in one subpopulation =	90–100%	95–100%	100%
(b) Extreme fluctuations in the number of mature individuals			

D. Very small or restricted population

	Critically Endangered	Endangered	Vulnerable
D. Number of mature individuals	< 50	< 250	**D1.** < 1,000
D2. *Only applies to the VU category* Restricted area of occupancy or number of locations with a plausible future threat that could drive the taxon to CR or EX in a very short time.	-	-	**D2.** typically: AOO < 20 km² or number of locations ≤ 5

E. Quantitative Analysis

	Critically Endangered	Endangered	Vulnerable
Indicating the probability of extinction in the wild to be:	≥ 50% in 10 years or 3 generations, whichever is longer (100 years max.)	≥ 20% in 20 years or 5 generations, whichever is longer (100 years max.)	≥ 10% in 100 years

1 Use of this summary sheet requires full understanding of the *IUCN Red List Categories and Criteria* and *Guidelines for Using the IUCN Red List Categories and Criteria*. Please refer to both documents for explanations of terms and concepts used here.

Table A4. IUCN Threat classification scheme

https://www.iucnredlist.org/resources/threat-classification-scheme

1 Residential & commercial development

1.1 Housing & urban areas

1.2 Commercial & industrial areas

1.3 Tourism & recreation areas

2 Agriculture & aquaculture

2.1 Annual & perennial non-timber crops

2.1.1 Shifting agriculture

2.1.2 Small-holder farming

2.1.3 Agro-industry farming

2.1.4 Scale Unknown/Unrecorded

2.2 Wood & pulp plantations

2.2.1 Small-holder plantations

2.2.2 Agro-industry plantations

2.2.3 Scale Unknown/Unrecorded

2.3 Livestock farming & ranching

2.3.1 Nomadic grazing

2.3.2 Small-holder grazing, ranching or farming

2.3.3 Agro-industry grazing, ranching or farming

2.3.4 Scale Unknown/Unrecorded

2.4 Marine & freshwater aquaculture

2.4.1 Subsistence/artisanal aquaculture

2.4.2 Industrial aquaculture

2.4.3 Scale Unknown/Unrecorded

3 Energy production & mining

3.1 Oil & gas drilling

3.2 Mining & quarrying

3.3 Renewable energy

4 Transportation & service corridors

4.1 Roads & railroads

4.2 Utility & service lines

4.3 Shipping lanes

4.4 Flight paths

5 Biological resource use

5.1 Hunting & collecting terrestrial animals

5.1.1 Intentional use (species being assessed is the target)

5.1.2 Unintentional effects (species being assessed is not the target)

5.1.3 Persecution/control

5.1.4 Motivation Unknown/Unrecorded

5.2 Gathering terrestrial plants

5.2.1 Intentional use (species being assessed is the target)

5.2.2 Unintentional effects (species being assessed is not the target)

5.2.3 Persecution/control

5.2.4 Motivation Unknown/Unrecorded

5.3 Logging & wood harvesting

5.3.1 Intentional use: subsistence/small scale (species being assessed is the target [harvest]

5.3.2 Intentional use: large scale (species being assessed is the target)[harvest]

5.3.3 Unintentional effects: subsistence/small scale (species being assessed is not the target)[harvest]

5.3.4 Unintentional effects: large scale (species being assessed is not the target)[harvest]

5.3.5 Motivation Unknown/Unrecorded

5.4 Fishing & harvesting aquatic resources

5.4.1 Intentional use: subsistence/small scale (species being assessed is the target)[harvest]

5.4.2 Intentional use: large scale (species being assessed is the target)[harvest]

5.4.3 Unintentional effects: subsistence/small scale (species being assessed is not the target)[harvest]

5.4.4 Unintentional effects: large scale (species being assessed is not the target)[harvest]

5.4.5 Persecution/control

5.4.6 Motivation Unknown/Unrecorded

6 Human intrusions & disturbance

6.1 Recreational activities

6.2 War, civil unrest & military exercises

6.3 Work & other activities

7 Natural system modifications

7.1 Fire & fire suppression

7.1.1 Increase in fire frequency/intensity

7.1.2 Suppression in fire frequency/intensity

7.1.3 Trend Unknown/Unrecorded

7.2 Dams & water management/use

7.2.1 Abstraction of surface water (domestic use)

7.2.2 Abstraction of surface water (commercial use)

7.2.3 Abstraction of surface water (agricultural use)

7.2.4 Abstraction of surface water (unknown use)

7.2.5 Abstraction of ground water (domestic use)

7.2.6 Abstraction of ground water (commercial use)

7.2.7 Abstraction of ground water (agricultural use)

7.2.8 Abstraction of ground water (unknown use)

7.2.9 Small dams

7.2.10 Large dams

7.2.11 Dams (size unknown)

7.3 Other ecosystem modifications

8 Invasive & other problematic species, genes & diseases

8.1 Invasive non-native/alien species/diseases

8.1.1 Unspecified species

8.1.2 Named species

8.2 Problematic native species/diseases

8.2.1 Unspecified species

8.2.2 Named species

8.3 Introduced genetic material

8.4 Problematic species/diseases of unknown origin

8.4.1 Unspecified species

8.4.2 Named species

8.5 Viral/prion-induced diseases

8.5.1 Unspecified "species" (disease)

8.5.2 Named "species" (disease)

8.6 Diseases of unknown cause

9 Pollution

9.1 Domestic & urban waste water

9.1.1 Sewage

9.1.2 Run-off

9.1.3 Type Unknown/Unrecorded

9.2 Industrial & military effluents

9.2.1 Oil spills

9.2.2 Seepage from mining

9.2.3 Type Unknown/Unrecorded

10 Geological events

10.1 Volcanoes

10.2 Earthquakes/tsunamis

10.3 Avalanches/landslides

11 Climate change & severe weather

11.1 Habitat shifting & alteration

11.2 Droughts

11.3 Temperature extremes

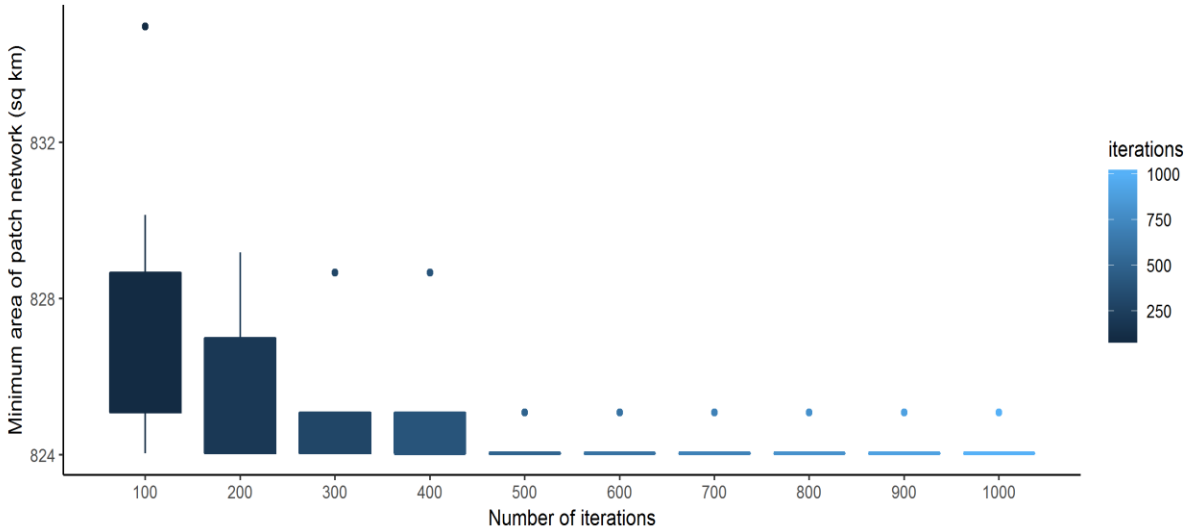
11.4 Storms & flooding

11.5 Other impacts

12 Other options

12.1 Other threat

Table A5. Testing iterations needed for greedy algorithm



We applied the greedy algorithm to a network of patches derived from 2 km buffers for all *Aloe* species. The algorithm reports the minimum patch area needed to achieve our target of representing each species. Each iteration of the algorithm could produce a different set of patches, and therefore a different minimum patch area, because when the highest number of species was tied between two or more patches, one patch was chosen at random. We ran the algorithm for 1,000 iterations and checked the minimum patch area that had been calculated at intervals of 100. We ran this procedure 10 times to get average, min and max values at each 100 iteration interval (see box plot). There was variation of up to 10 km in minimum patch area after 100 iterations, but this steadily decreases as the number of iterations increases. The minimum is achieved after 500 iterations with a variation of 1 km from the minimum, which was deemed of sufficient accuracy for the purposes of the analysis. As the algorithm was not particularly process intensive, there was no significant cost of running the algorithm for 1,000 iterations.

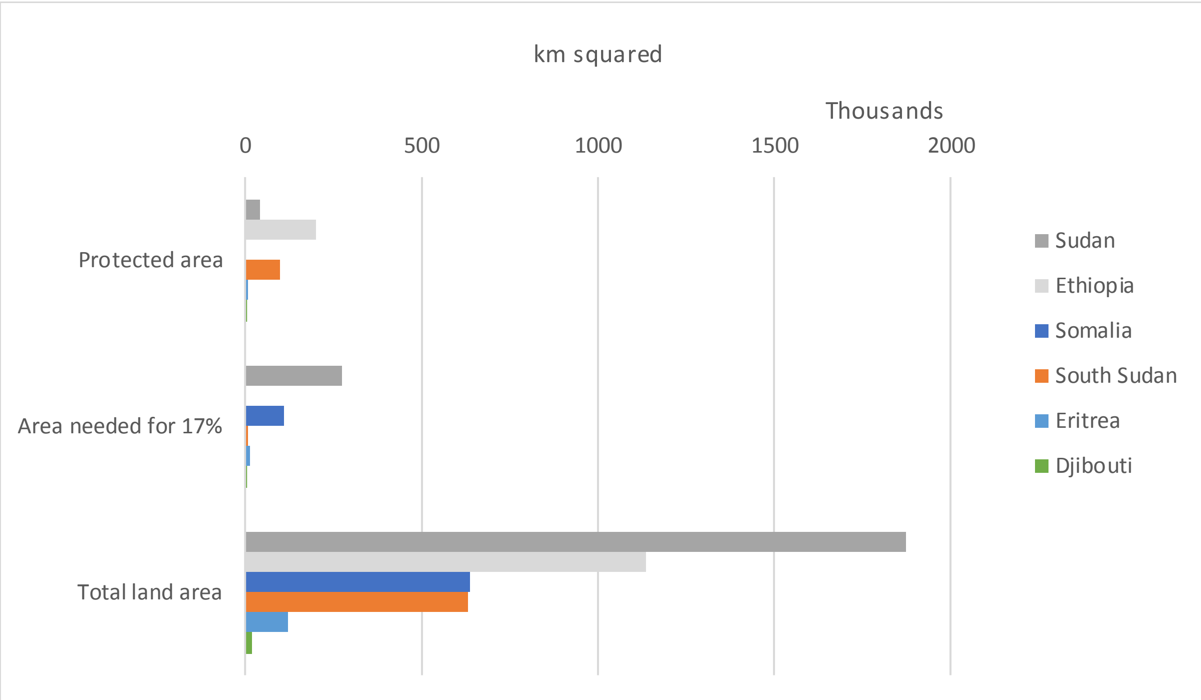
Table A6. Final sequence of patches for all species and threatened species

A6a – all species			A6b – threatened and DD species	
Minimum area:	824.0306		Minimum area:	541.5795
Iteration number:	117		Iteration number:	169
	Patch ID			Patch ID
1	430		1	430
2	444		2	444
3	388		3	168
4	498		4	362
5	269		5	361
6	362		6	374
7	221		7	309
8	168		8	274
9	262		9	526
10	349		10	394
11	166		11	498
12	37		12	414
13	414		13	272
14	407		14	355
15	78		15	220
16	91		16	449
17	459		17	174
18	476		18	223
19	220		19	266
20	406		20	416
21	437		21	221
22	135		22	365
23	527		23	408
24	223		24	407
25	355		25	230
26	423			
27	417			
28	425			
29	384			
30	416			
31	378			
32	408			
33	365			
34	212			
35	445			
36	501			
37	102			

38	266	
39	272	
40	394	
41	453	
42	278	
43	515	
44	172	
45	230	

Table A7. Protected areas per country

Country	% protected	Protected area	Area needed for 17%	Total land area
Sudan	2.28	42698	275415	1871252
Ethiopia	17.62	200074	0	1135429
Somalia	0	0	108401	637655
South Sudan	15.5	98214	9495	633580
Eritrea	4.87	5936	14776	121834
Djibouti	1.57	344	3369	21844



Data derived from WDPA (UNEP-WCMC and IUCN 2018). In the table and chart the text 'Area needed for 17%' refers to the Convention on Biological Diversity's (CBD) Aichi Target 11 to conserve 17% of terrestrial land that is '...of particular importance for biodiversity...' (UNEP/CBD 2010).

Table A8. ***Aloe*** **species in botanic garden collections (See separate excel file)**

https://github.com/stevenpbachman/thesis_extra/blob/master/A8_ex%20situ%20collections.csv

Table A9. Number of banked collections of *Aloe* in the Millennium Seed Bank grouped by threatened (6) and not threatened species (8). Non-banked species were grouped by threatened (25), not threatened (40), and data deficient (9) species.

Threat Status	Collection status	Count
Data Deficient	Not banked	9
Not threatened	Banked	8
Not threatened	Not banked	40
Threatened	Banked	6
Threatened	Not banked	25

References:

UNEP-WCMC and IUCN (2018) The World Database on Protected Areas (WDPA) [On-line]. In: Cambridge, UK. www.protectedplanet.net.

UNEP/CBD (2010) The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. In: UNEP/CBD/COP/DEC/X/2. https://www.cbd.int/decision/cop/?id=12268.

C. Appendices

Appendix 1 – State of the World's Plants Report 2016

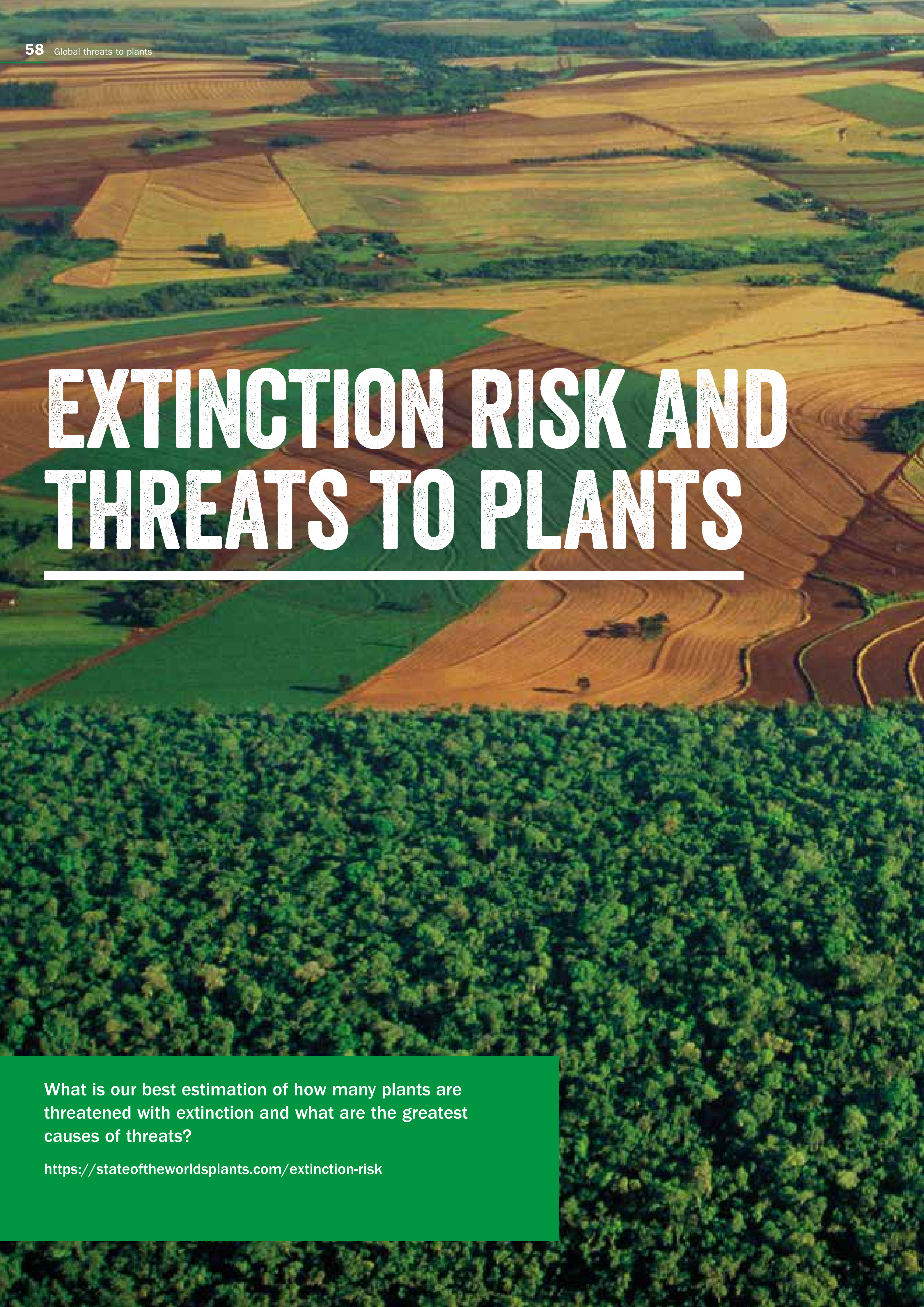
Appendix 2 - Brummitt et al. 2008

Appendix 3 - Darrah et al. 2017

Appendix 4 - Rakotoarinivo et al. 2014

Appendix 5 - Bachman_GSPC_2_poster

Appendix 6 - ThreatAssessR



EXTINCTION RISK AND THREATS TO PLANTS

What is our best estimation of how many plants are threatened with extinction and what are the greatest causes of threats?

https://stateoftheworldsplants.com/extinction-risk

ONE IN FIVE

PLANTS ARE ESTIMATED TO BE THREATENED WITH EXTINCTION

EXTINCTION IS AN ABSOLUTE TERM, MEANING THAT NO INDIVIDUAL OF A SPECIES REMAINS ALIVE.

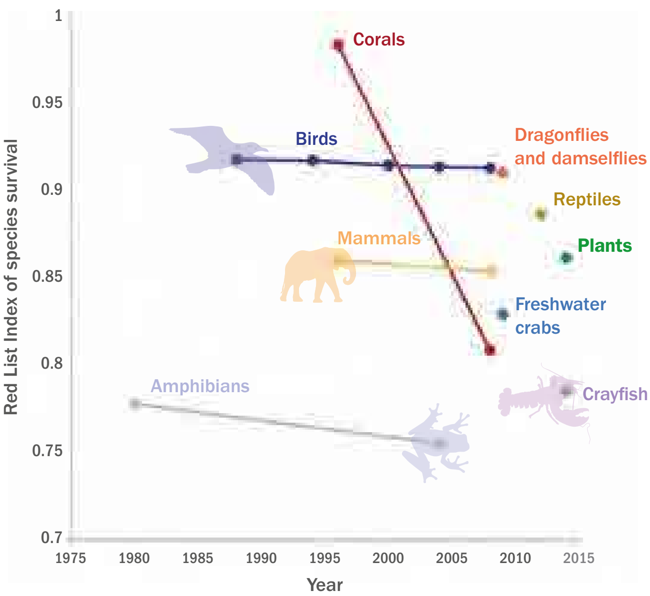
In practice extinction is hard to prove, because a species of plant that appears to be extinct may actually persist in the form of a very small number of individuals. Owing to difficulty in detection of some individuals (such as a rare orchid that only flowers every ten years and is hard to identify when not in flower), or a lack of survey effort (imagine a remote area that is hard to access and has received little attention from botanists), the few remaining individuals of a rare species may remain unobserved and the species recorded as extinct. With concerted effort or a chance finding, these species may be 're-discovered'. In the event of re-discovery, these apparently extinct species are labelled as 'Lazarus' species, touching on the biblical reference to Jesus raising Lazarus from the dead (see Box 10).

The alternative to the binary classification of extinct/extant, is to estimate the probability of extinction so that action can be taken while species decline is still reversible. This is the approach that the *IUCN Red List of Threatened Species* adopts. The Red List collates the work of a large team of specialists from all over the world who assess different groups of organisms, including plants, and score them against quantitative criteria based on parameters such as population reduction and restricted geographic range. These criteria are chosen because they reflect the symptoms of imminent extinction, and, importantly, because they can be estimated from partial or uncertain information. These data are then used to classify a species into a category ranging from extremely high risk of extinction (e.g. Critically Endangered) to little or no risk (e.g. Least Concern). In some cases, there are insufficient data to assess the status, in which case a species is labelled as Data Deficient. The resultant list tells conservationists which species are high risk, low risk, or in need of further investigation. It is a vital resource for conservation. Entire groups of organisms (e.g. birds and mammals) have been assessed in this way. In addition, these extinction risk assessments include documentation of the threatening processes affecting plants (see Figure 19): analysis of the existing Red List of plants shows that the conversion of land for agriculture is the dominant threat, followed by biological resource use.

A REPRESENTATIVE LIST OF RISK

Over 20,617 assessments of extinction risk for vascular plant species have been carried out and published on the Red List. This represents a quarter of all species on the Red List, but only around 5% of all plants. This small sample is also skewed for various reasons, notably because assessors mostly select species that are likely to be at risk of extinction.

FIGURE 17: RED LIST INDEX VALUE OF SPECIES SURVIVAL FOR PLANTS IN COMPARISON WITH OTHER GROUPS



A value closer to 1 indicates most species in the group are at low risk, a value towards 0 indicates species that are moving towards extinction. Values for crayfish, freshwater crabs, dragonflies and damselflies, reptiles and plants are based on a sampled approach.

REPRODUCED WITH PERMISSION FROM BRUMMITT ET AL. (2015) [32]

FIGURE 18: VARIATION IN PUBLISHED ESTIMATES OF THE PERCENTAGE EXTINCTION RISK OF PLANTS

% of plants estimated to be at risk	Year of estimate
10%	1978
24%	1985
27%	1987
12.5%	1998
33.33%	1999
15–20%	2002
22–62%	2002
20%	2008
27–33%	2010
20%	2011
30%	2014
27–33%	2015
20%	2015

For a full description of the data sources used please refer to the supplementary material online at: http://stateoftheworldsplants.com/extinction-risk

BOX 10: BACK FROM THE BRINK? AN EXTINCT IN THE WILD (EW) TREE RE-DISCOVERED

The 'guarajuba', *Terminalia acuminata* (Combretaceae), is a magnificent Brazilian hardwood timber tree, endemic to a narrow patch of Mata Atlantica (Atlantic Forest) in Rio de Janeiro, Brazil. The species was once considered abundant in the surroundings of Brazil's second biggest city and it was first formally described in 1867. The high quality of its timber and vast array of carpentry uses led to relentless over-exploitation, driving the species to the verge of extinction. In fact, it was listed as 'Extinct in the Wild' (EW), with only five living specimens known to exist in the Rio de Janeiro Botanic Garden. In 2015, *T. acuminata* was rediscovered, 80 years after it was last seen in the wild, less than 50 km from the botanic garden. The species is currently assessed as 'Endangered' (EN) by the 'Official National Brazilian Threatened Flora Species List (2014)' (http://cncflora.jbrj.gov.br/portal/static/pdf/portaria_mma_443_2014.pdf) although this assessment will need to be reviewed in the light of new data from ongoing fieldwork. The re-discovery of this enigmatic tree shocked the Brazilian conservation community and represented a significant milestone in the conservation of the Atlantic Rainforest biome.

Analysis carried out for this report reveals that the orchid (Orchidaceae), mint (Lamiaceae) and heather (Ericaceae) families are all under-represented on the Red List. There has been notable recent progress towards the goal of generating a full Red List for all plants [50]. Ambitious plans are underway to tackle major groups of plants such as trees (see Box 11), but sadly the lack of coverage of plants means that the Red List does not yet adequately represent overall extinction risk in plants. We reviewed published estimates of the proportion of plants that are threatened with extinction, which show considerable variation and reflect our uncertainty (see Figure 18).

A solution to a potential bias towards species at high risk is to take a suitably large, random selection of plant species and assess their extinction risk. This representative view of extinction risk in plants has revealed that one in five plant species are estimated to be in the top three 'threatened' categories of Critically Endangered, Endangered or Vulnerable [32]. Further assessments of the sample in future years will establish an overall trend in the extinction risk index for plants.

WHAT NEXT FOR EXTINCTION RISK ASSESSMENTS?

Clearly there is a need to expand the coverage of threat assessments and to speed up the process of assigning plant species an extinction risk rating, while ensuring scientific rigour [175]. Promising advances in the field of Earth Observations, including the opening up of global datasets with long-time series (such as maps of forest loss), will enable more quantitative analysis to support assessments, in particular declines over time [106, 176, 177]. The increase in digitisation of specimen data from the world's herbaria, and access to global species-occurrence data through services such as the Global Biodiversity Information Facility (http://www.gbif.org), has also meant that analysis can be based on a more complete knowledge of observation records over time and can allow the use of statistical models to estimate population declines [178] (see Figure 17). These methods have further potential to detect trends in species populations when combined with the scalability of opportunistic data from citizen science initiatives [179]. In summary, there is an urgent need to gain a more thorough understanding of which plants are threatened and where, so that conservation initiatives can be effective and plants can be saved well before they become candidates for extinction.

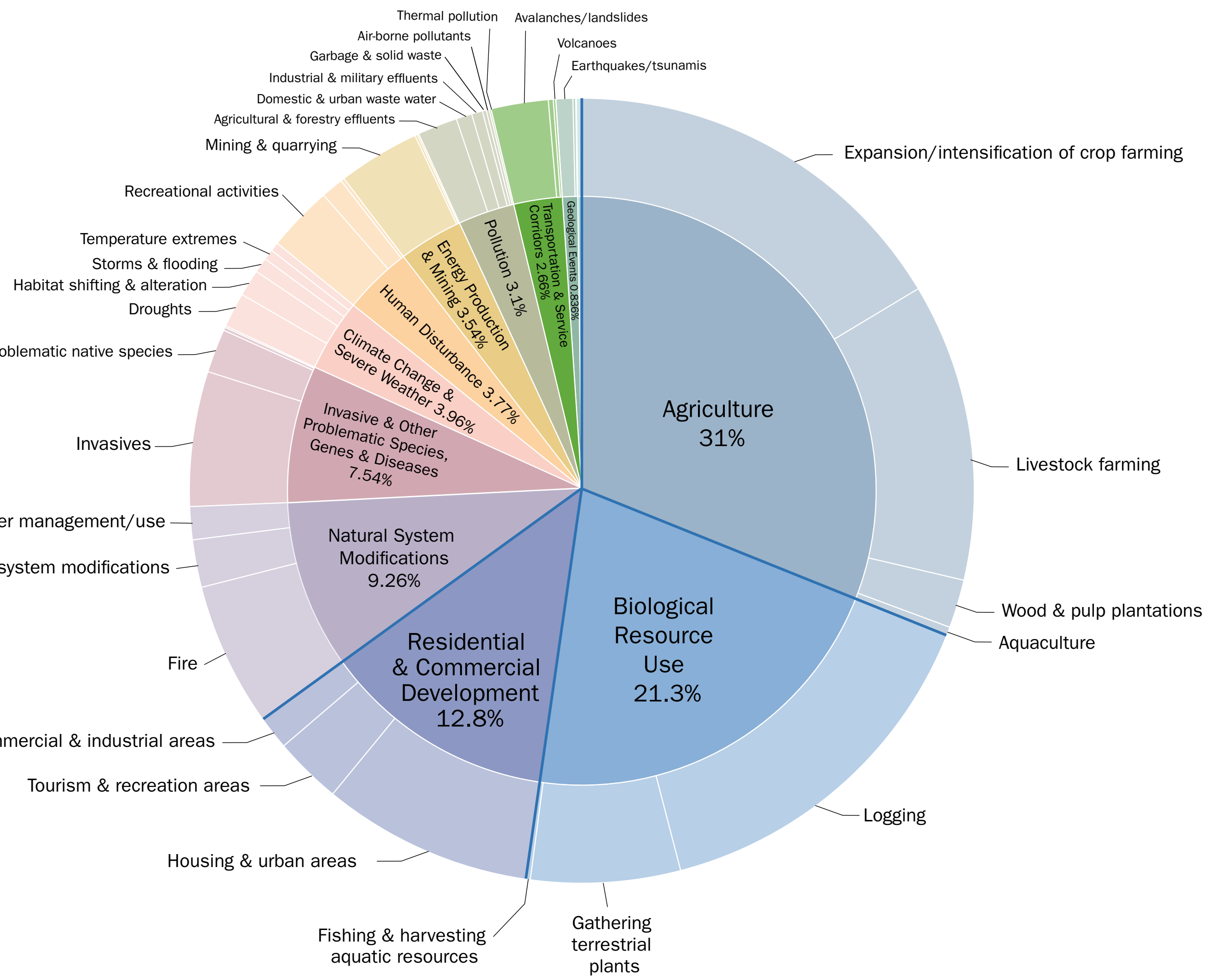
BOX 11: GLOBAL ASSESSMENT OF ALL TREES

Trees are an essential component of plant diversity, underpinning ecosystems and supporting livelihoods. Ongoing forest loss is threatening the world's trees, but an important new initiative, the 'Global Tree Assessment', has set a target of undertaking conservation assessments for all of the world's tree species by 2020 in order to prioritise conservation actions. Progress has already been made with several groups, including birch, magnolia, oak and maple, and there is a regional focus on the trees of Central Asia, the Mexican Cloud Forest and the Tropical Andes. Work is presently underway on timber trees, the trees of Europe and the Red List of Theaceae – the family which includes the tea plant, *Camellia sinensis*. Theaceae also includes some economically important timbers and ornamental species.

In conjunction with activity on Red List assessments of tree species, efforts are underway to collect and safely store the seeds of threatened trees. The Global Tree Seed Project aims to collect the seed of 3,000 of the world's most threatened tree species for long-term conservation in Kew's Millennium Seed Bank.

https://www.bgci.org/plant-conservation/globaltreeassessment/
http://science.kew.org/strategic-output/banking-worlds-seeds

FIGURE 19: SUNBURST DIAGRAM SHOWING BREAKDOWN OF THREATENING PROCESSES FOR VASCULAR PLANT SPECIES ASSESSED ON THE IUCN RED LIST



The first level of threat classification is shown in the inner circle with percentage of species subject to each threat. The outer ring shows the second level of threat. Threat classification is modified from the IUCN-CMP Unified Classification of Direct Threats. (See website for enhanced interactive version of these data: https://stateoftheworldsplants.com/extinction-risk)

OVER 20,617 ASSESSMENTS OF EXTINCTION RISK FOR VASCULAR PLANT SPECIES HAVE BEEN CARRIED OUT AND PUBLISHED ON THE IUCN RED LIST, BUT THIS ONLY REPRESENTS AROUND 5% OF ALL VASCULAR PLANTS

Vol. 6: 127–135, 2008
doi: 10.3354/esr00135

ENDANGERED SPECIES RESEARCH
Endang Species Res

Printed December 2008
Published online November 17, 2008

Contribution to the Theme Section 'The IUCN Red List of Threatened Species: assessing its utility and value'

OPEN ACCESS

AS WE SEE IT

Applications of the IUCN Red List: towards a global barometer for plant diversity

Neil Brummitt*, Steven P. Bachman, Justin Moat

Royal Botanic Gardens, Kew, Richmond, Surrey TW9 3AB, UK

ABSTRACT: The scale of the global biodiversity crisis means that international efforts to identify, conserve and monitor threatened species must be carried out at a greater speed than ever before. Recent developments in information technology present an opportunity to speed up the production of species conservation assessments, and methods and prospects for this are discussed in the context of the work being conducted on plant assessments for the International Union for Conservation of Nature (IUCN) Sampled Red List Index. The need for an internationally agreed upon, comparable, standardised system such as the Red List is emphasised here, but ultimately more efficient techniques must be developed to supplement the existing approach if this is to be able to meet the global demand.

KEY WORDS: IUCN · Red List · Plants · Sampled Red List Index · SRLI · Geographical Information System · GIS

INTRODUCTION

It is widely agreed that we are now in the middle of the sixth great mass extinction of life on this planet. However, what is less commonly known by the general public but is more worrying is how little we, the scientific and conservation community, actually know about exactly what we are losing and how quickly. Which species are most at threat? Where are those threats greatest? What are those threats? Tremendous progress has been made recently in fields such as systematics, biogeography, population genetics, remote sensing and conservation biology itself. However, the same impediments that have existed since the adoption of the Convention on Biological Diversity (CBD) in 1992, the first truly global initiative to legislate for the need to conserve biological diversity, continue to hamper efforts to fully understand, monitor and conserve our planet's biological diversity: there is too little knowledge, there are too few scientists, there is not enough money, and we are running out of time.

At present we are only really guessing at the extent to which the world's flora is threatened and whether this risk is increasing or not. Attempts have been made at an objective estimate to the first part of this question (Pitman & Jorgensen 2002), but without a comprehensive list of accepted species names and synonyms for the world's plants, estimates even just of total species of plants based on extrapolation from either partial checklists (Govaerts 2001, 2003) or on patterns of endemism (Bramwell 2002) are subject to a high degree of unquantifiable error (Ungricht 2004). However, many groups of plant species have been the focus of recent efforts to produce modern, authoritative taxonomic checklists, and international progress on this issue is encouraging, with the majority of species now thought to have been treated (Paton et al. 2008). The next step is to quantify the threat of extinction for species in these groups. Overall threat status has been inferred from global lists of threat such as the International Union for Conservation of Nature (IUCN) Red List (e.g. Walter & Gillett 1998), but this sample is biased and not representative. Consistent assessments at the species level also allow trends over time to be identified as species move between categories (Butchart et al. 2004, Baillie et al. 2008) and therefore

*Email: n.brummitt@kew.org

will help to answer the second part of the question — How is the level of threat to the world's flora changing over time?

To date, there are 12 043 plant species assessed according to the IUCN Categories and Criteria as listed in the 2007 IUCN Red List of threatened species (www.iucnredlist.org, accessed on 3 January 2008). This is a mere 3.2% of the estimated number of currently known plant species (379 881; Paton et al. 2008), and is not a representative sample of species, most samples being those for which there happens to be an active Specialist Group (e.g. conifers, cycads), regional strength (e.g. South Africa), or a strong economic interest (e.g. trees; Oldfield et al. 1998). Most species have not been assessed as to their conservation status, and for the majority of known species there is currently insufficient baseline information with which to make that assessment. This is in stark contrast to knowledge of the world's bird species, for example. However, birds and other vertebrate groups must be seen as comparatively small, anomalously well-known taxa. There are more species of grasses than there are bird species worldwide, but far more ornithologists than there are agrostologists, or even botanists in general.

For the majority of plant species already described, especially for those in the biodiversity hotspots in the tropics, all that is known for each species is the original description and Latin diagnosis, plus at least 1 cited specimen (the holotype) and, if known, sometimes a brief summary of its broader distribution (Nic Lughadha et al. 2005). For many countries around the world, there is still no modern, complete Flora for all of the plant species found there, nor is there even an up-to-date and comprehensive checklist (Frodin 2001, Paton et al. 2008). Few species are really known in any detail — there is almost no existing information on numbers of individuals, numbers of separate populations, breeding success (or even breeding system), dispersal capability, or known or potential economic uses, let alone any population genetic studies or detailed understanding of gene flow patterns. For most plant species the most comprehensive, easily accessible information, and the most reliable data on which to base a species conservation assessment, is of the location and range of that species, the best source of which is the dried plant specimens held collectively in the world's herbaria.

PROBLEMS IN APPLYING THE IUCN CATEGORIES AND CRITERIA TO PLANTS

The IUCN system of classifying extinction risk to species (IUCN 2001) is now well established as the most comprehensive, quantitative and widely used method for determining threat of extinction to species (Rodrigues et al. 2006). The product of the system, the Red List, is a list of species ranked according to their relative risk of extinction, and the associated species assessments compile the current knowledge of the conservation status of and threats to that species. The list is an extremely valuable tool for informing species and site level conservation efforts; it is recognised around the world by both specialists and non-specialists alike. So why have so few plants been assessed so far using the IUCN system? Several overlapping issues provide perhaps the major reason for the lack of plant species listed on the Red List. An unfortunate consequence of making the IUCN Categories and Criteria more quantitative and objective is that fewer plant species can be assessed; there simply are not enough experts and there is insufficient knowledge of most plant species to apply the criteria. Many groups of plants are thus not currently being actively studied and/or last received critical attention decades ago, so further information is unlikely to be forthcoming within a short period of time. A major, but perhaps not as obvious, reason for a poor showing of plants on the Red List is that this is not the only system for classifying species at risk of extinction. In the United States the NatureServe system (www.natureserve.org/explorer/ranking.htm) is primarily used, and over 62 000 plant taxa have already been assessed in that system. Variations on the Red List system also exist, for example in New Zealand (Hitchmough 2002), and other alternative systems are also available, such as the Genetic Heat Index (Hawthorne 2001). In other words, assessments are being made, but not necessarily within the IUCN system. Combine this with the taxonomic impediment already highlighted and a lack of recent Floras or checklists for most regions of the world, and it is no wonder that plants are poorly represented on the Red List.

Another reason for the apparent lack of plant assessments is the formulation of the IUCN Categories and Criteria themselves. The system has been modified over the years from the early subjective criteria (Fitter & Fitter 1987) to the thoroughly rigorous, quantitative and data-driven version that exists today (IUCN 2001). Sadly, plant assessments made with the old criteria (e.g. Walter & Gillett 1998) are now obsolete, and, in order to be listed again on the Red List, they must be re-assessed with the new version of the IUCN Categories and Criteria. Although a possible explanation, this may no longer be an excuse for a lack of plant assessments. The IUCN considers assessments that are 10 yr old to be out of date and due for re-assessment. Many plants assessed using older versions of the Categories and Criteria should now be close to or already due for a re-assessment. Although there are bound to be minor modifications, the present version of the Categories and Criteria (Version 3.1; IUCN 2001) is not expected to change in the near future (IUCN 2006). The IUCN specialist groups also have a significant influence on which and how many species are assessed. It is no surprise that active groups, such as the Conifers and Cycads Group, have completed assessments of their entire respective groups and, in some cases, have produced assessments on more than one occasion. Each specialist group acts as a focal point for a network of experts and can encourage knowledge and data transfer through websites and mailing lists to allow more assessments to be carried out. The work of the members of the specialist groups is, of course, voluntary, in addition to other commitments, and can take up a significant amount of time. At present a shortage of volunteers exists for these groups, which has resulted in a lack of coverage of many of the world's plants; there are currently 29 groups (www.iucn.org/themes/ssc/sgs/plants.htm), but major areas of plant diversity, including large taxonomic groups, such as the Asteraceae (the daisy family), estimated to include some 23 600 species (Stevens 2008), and geographical areas, most conspicuously among them, tropical forests, remain unrepresented.

However, there are several important points to note about the new Categories and Criteria that may allow more plant assessments to be made. The IUCN discourages the liberal use of the Data Deficient (DD) category, the rank used when there is inadequate information to make a direct, or indirect, assessment of extinction risk to a species, arguing that, in many cases, poorly known taxa can be assessed based on background information relating to threats, e.g. habitat loss or other causes (IUCN 2006). In essence, a threat or decline does not necessarily have to be observed in order for an assessment to be carried out; for some criteria it is enough to infer or suspect. In fact, a species can even be listed based on projected future threats. However, the extent to which inferences and projections can be used should be carefully considered (see the IUCN guidelines for discussions on data uncertainty; IUCN 2006). Another way in which data-poor species may be assessed is by using information from better known and closely related species. Some plants are well studied and their conservation status is well known for a variety of reasons: economic or livelihood value, most obviously crop wild relatives; rarities and oddities, such as carnivorous plants; or 'flagship' species such as the slipper orchids (subfamily Cypripedioideae). If information on population density and dispersal distance from these well studied taxa could be used for other species within a similar taxonomic or biological grouping, this would be one possible approach to obtaining the necessary information for carrying out a thorough conservation assessment.

GLOBAL INITIATIVES — GSPC TARGET 2

An ambitious attempt to accelerate the production of preliminary plant conservation assessments, and to galvanise the existing efforts of the world's botanists and plant conservationists into doing so, is the Global Strategy for Plant Conservation (GSPC) (UNEP 2002a) and the 16 quantitative targets set out within it. The targets of the GSPC were adopted at the 6th Conference of the Parties (COP) to the CBD in 2002 (COP Decision VI/9, www.cbd.int/decisions/cop6/?m=COP-06&id=7183&lg=0), and these targets were originally set to be achieved by 2010. It includes as its Target 2, for which the IUCN is the facilitating stakeholder, the production of 'a preliminary assessment of the conservation status of all known plant species' to highlight those of potential conservation concern (Target 1, on which many of the other targets rely, is the production of a global plant checklist; see Paton et al. 2008 for a review of progress towards Target 1). Target 2 is obviously an enormously challenging task, towards which disappointingly little progress has been made so far, and the prospects of much of this work being completed by 2010 seem remote. To date, much discussion has centred on just how these preliminary conservation assessments will be carried out, and it is proposed to use the Rapid List software (http://iucnsis.org/RapidList/org.iucn.rapidlist.RapidList/RapidList.html), which guides the user through a series of 7 questions to indicate whether or not a species is likely to fall into any of the 'Threatened' categories, but without capturing explicit quantitative data on either range size or population size. These assessments are thus deliberately preliminary, as a first step towards full assessments of the threatened species, and will not in themselves be sufficient for inclusion on the IUCN Red List. However, to date only a small proportion of species have received even a preliminary assessment.

PRELIMINARY CONSERVATION ASSESSMENTS

There is a clear need to drastically increase the rate at which we produce species conservation assessments. If GSPC Target 2 is to stand any chance of being met, a coherent approach to preliminary assessments is required. Callmander et al. (2005) argue that information derived from herbarium specimen labels is often sufficient for a preliminary assessment. For a 'first-cut' towards GSPC Target 2 there should be sufficient information to group plant species into 'threatened/potentially threatened' or 'not threatened' categories. Herbarium specimens provide verifiable records indicating the existence of taxa at a given time and place, assuming both are recorded, and, in common with the rise in museum- and herbarium-based informatics (Burgman et al. 1995, Ponder et al. 2001, Graham et al. 2004, Roberts et al. 2004), we have developed automated tools for carrying out conservation assessments (see also Willis et al. 2003). Certain parameters within the IUCN criteria lend themselves to calculation within a geographical information system (GIS); by simply collating known specimens for a species and plotting them on a map, it is possible to calculate values for area-based measures such as extent of occurrence (EOO), area of occupancy (AOO) and number of subpopulations (IUCN 2001; our Fig. 1).

By comparing these measures against the thresholds set in the IUCN criteria under Criterion B, a category of threat can be obtained. These GIS assessments should be described as preliminary, since they also need to satisfy at least 2 out of 3 subcriteria, but can already count towards the GSPC target. It is important to note that the 'first-cut' GSPC assessments will simply split species into 2 general groups: 'threatened/potentially threatened' and 'not threatened' so that attention can be focused on the first group. The preliminary GIS assessments go a step further by providing quantitative data that can actually be used for a full IUCN assess-

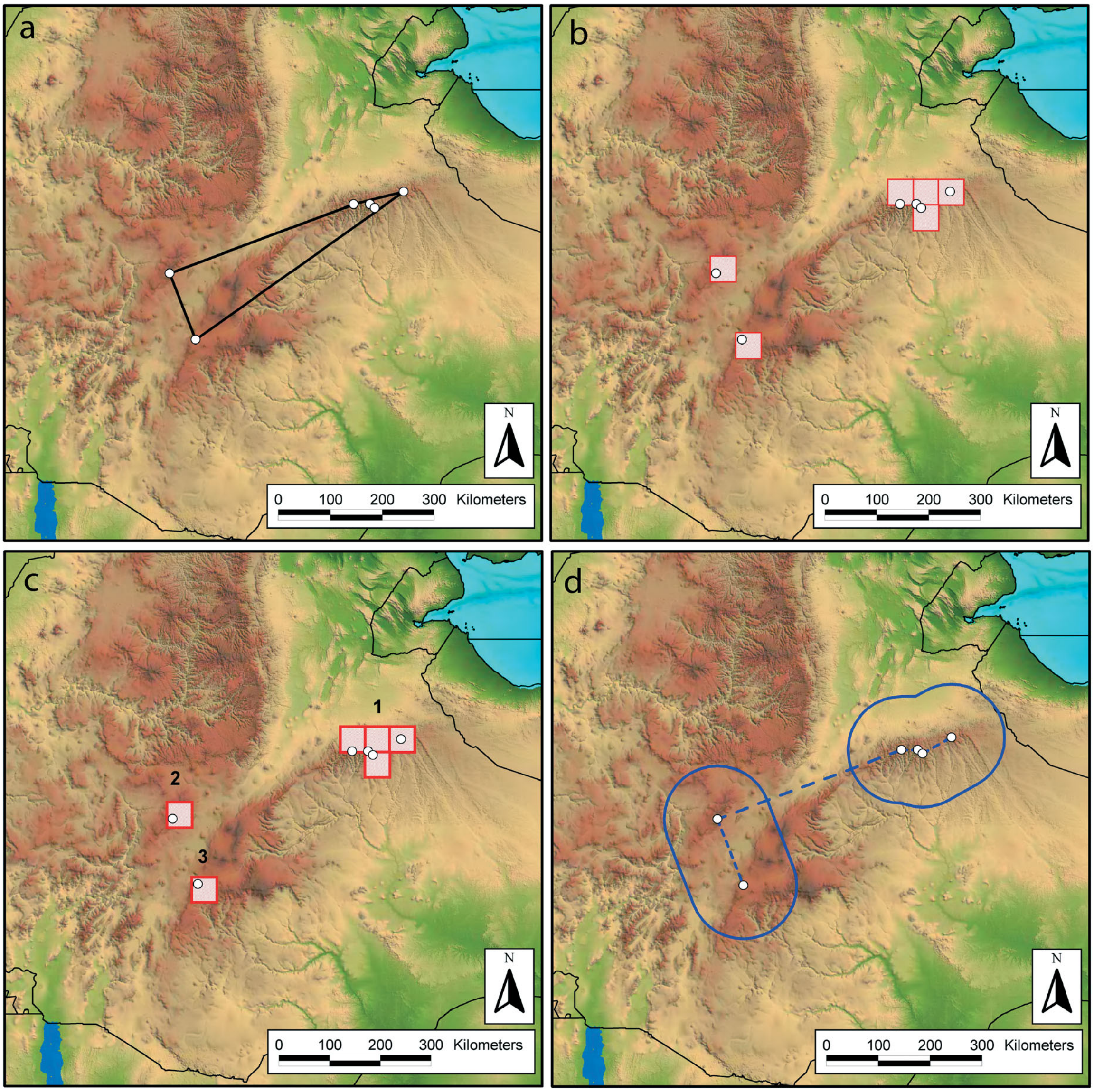


Fig. 1. Automated preliminary GIS analysis of *Aloe pubescens* Reynolds from the highlands of Ethiopia using georeferenced specimens from the herbarium at the Royal Botanic Gardens, Kew, showing (a) the extent of occurrence, measured as a convex hull; (b) the area of occupancy, measured with a cell width of 48 km; (c) the number of subpopulations using the cell-adjacency method of Schatz et al. (2000); and (d) the number of subpopulations using Rapoport's principle of mean propinquity (Rapoport 1982; see also Willis et al. 2003)

ment, although only when all subcriteria are satisfied and subsequently verified can the assessment be classified as 'full' and therefore included on the Red List. These tools can now be downloaded from the Royal Botanic Gardens (RBG), Kew, GIS Unit website as an ArcView extension (www.kew.org/gis/projects/ cats).

To date, the preliminary GIS assessments have been successfully applied to a variety of taxa across systematic groups and over a broad geographic range. The tools are commonly utilised within RBG Kew (Utteridge et al. 2005, Davis et al. 2006, Rico Arce & Bachman 2006) and Missouri Botanical Garden (Callmander et al. 2007) and have been used elsewhere by counterparts from collaborating institutions. One of the major advantages of the technique is the fact that it is automated; at the click of a button a series of values including EOO and AOO, along with a preliminary rating, can be returned. Furthermore, a batch facility allows multiple species to be assessed in one run. If georeferenced specimen data existed for all plants it would be possible to calculate preliminary assessments in a matter of minutes and GSPC Target 2 would be accomplished. The only prerequisite is a database of error-checked, georeferenced specimens — a commodity that is becoming increasingly available as many herbaria are in the process of converting their collections to electronic format. As well as utilising historical collections, it is possible for contemporary and future collections to be used for the preliminary GIS technique. The majority of contemporary specimen collections are now accompanied by a global positioning system derived co-ordinate that should place the specimen collection to within metres of accuracy. At present, the Global Biodiversity Information Facility (GBIF; www.gbif.org/) is already serving up 136 million collections, 81 million of which are georeferenced; obviously not all are plants, but the automated preliminary assessment tool can be equally well applied to animal species.

Clearly one would like to assess the accuracy of preliminary conservation ratings produced in this way, but this has proved difficult to test, as it is not easy to find species that have been fully assessed (listed on the Red List) and also have complete, georeferenced specimen collections. However, one example for which both exist is in the cypress family (Cupressaceae; Farjon 2005) of conifers. The IUCN Conifer Specialist Group is one of the major, active plant groups and has been successful in assessing all conifers, excluding those with taxonomic uncertainties (Farjon et al. 2006). A database for Cupressaceae compiled as part of the efforts to produce a taxonomic monograph (Farjon 2005) contains a comprehensive collection of georeferenced specimens of the cypress family, which have a global distribution and a range from Critically Endangered (CR) to Least Concern (LC) status and so form an ideal dataset with which to test the accuracy of the preliminary GIS assessments. Taxa were grouped into either 'Threatened' (CR, Endangered [EN], or Vulnerable [VU]) or 'not Threatened' (Near Threatened [NT] or LC) for both full and preliminary assessments. The extent to which the preliminary assessments were correct (accurately discriminated Threatened and non-Threatened taxa), overestimated threat status (not Threatened classed as Threatened), or underestimated threat status (Threatened classed as not Threatened) when compared with an expert assessment of that species is shown in Fig. 2. For nearly three-quarters of the species, the preliminary estimates correctly classified the full assessment.

The preliminary GIS approach can be criticised for only considering 1 aspect of an already contentious issue within the IUCN Categories and Criteria — range size. Considerable debate has taken place regarding the area measures used by the IUCN, particularly the imposition of a standard cell size for measuring AOO regardless of the size of EOO; a full 10 pages are dedicated to the explanation of EOO and AOO alone in the present guidelines to the Categories and Criteria document (IUCN 2006). An obvious omission from the preliminary analysis is the lack of population information. Geo-referenced specimens may represent a single individual or a population numbering 1000s of individuals. Only with adequate ground-truthing, surveying sizes and status of populations in the field can this information be obtained. The quality of georeferencing is a crucial consideration when dealing with area-based measures derived from specimen data; a species range could be miscalculated by 100s of km^2 if a specimen is inaccurately located (Miller et al. 2007). A 'clean' dataset is required, which means any outliers or georeferencing errors must be removed before carrying out the assessment; guidelines (Chapman & Wieczorek

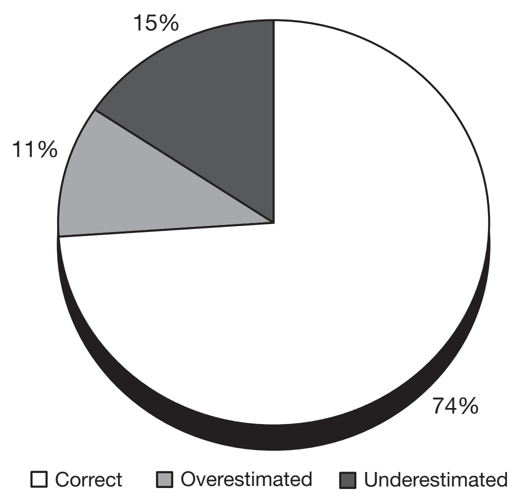


Fig. 2. Comparison of automated preliminary and full Red List assessments for Cupressaceae

2006) and resources (www.herpnet.org/Gazetteer/GeorefResources. htm) are already available to aid the georeferencing process, and many gazetteers now exist in electronic form to make georeferencing easier and quicker. There are even tools to automatically calculate the error associated with a georeference (Guralnick et al. 2006), an important measure that is often neglected, as imprecisely georeferenced specimens may need to be excluded from the analysis.

'DESKTOP' CONSERVATION ASSESSMENTS

The preliminary assessment can also be the basis for a full assessment, and, if checked for error, georeferenced herbarium specimen data can be provided; further GIS techniques then provide a means by which these assessments can be carried out. The preliminary techniques developed at RBG Kew (Willis et al. 2003) have now been extended into a more detailed methodology. This 'desktop' technique has developed in response to the need for assessments to be made on a variety of taxa from a wide variety of geographic areas. The 'desktop' assessor attempts to determine as much assessment-relevant information as possible about a species by trawling the literature, examining information from specimen labels, incorporating GIS techniques and (where data permits) statistical models, as well as contacting experts. To date, IUCN Red List assessments have mostly been carried out by the experts of a particular group, but we feel strongly that assessments can be compiled by non-experts, as long as they have a thorough understanding of the IUCN Categories and Criteria, a database of georeferenced specimen collections and some basic GIS knowledge. GIS techniques have already proven valuable for preliminary results, but more detailed analysis can still provide more useful information for assessments, filling the gaps when experts, specimen labels, or literature cannot provide enough information. Often this GIS analysis is enough to estimate fragmentation, number of locations and continuing decline or extreme fluctuations in range, habitat, or number of locations or subpopulations and so provide the data for a full assessment under Criterion B.

For example, a species may only be known from a single collection and by default will be treated as DD by the GIS algorithm, as neither EOO nor AOO can be automatically calculated, but it may still be possible to make an assessment by considering the area where the collection was made, the present threats in that area and how it may have changed over time. By simply querying various GIS layers at the known specimen localities, or within specified error buffers, it is possible to find out habitat preferences (GLC2000, www.gvm.jrc.it/glc2000; Bartholomé & Belward 2005), elevation range (GTOPO 30, edcdaac.usgs.gov/gtopo30/gtopo30.htm, or SRTM, www2.jpl.nasa.gov/srtm/), human impact (Human Footprint, www.ciesin.columbia.edu/wild_areas/), level of protection (WDPA, www.unep-wcmc.org/wdpa/), type of Ecoregion (WWF Ecoregions, www.worldwildlife.org/science/ecoregions.cfm), fire activity (MODIS fire data, modis-fire.umd.edu/ data.asp), as well as climate preferences (WORLDCLIM, www.worldclim.org/). GIS data derived from remote sensing imagery can also be useful for assessments; for example, changes in land cover can be used to infer or estimate reductions and declines of EOO, AOO, or habitat (Buchanan et al. 2008). GIS data and modelling techniques in the form of ecological niche models (ENM; Peterson et al. 2002) can also be used to provide a more refined estimate of range for both EOO (Sérgio et al. 2007) and AOO (IUCN 2006), as long as models are validated and represent occupied habitat. ENMs have also been used to project species distribution ranges into future climates to see how ranges might change and how this affects Red List status (Bomhard et al. 2005). These 'desktop' assessments are then sent to experts and specialists for their review and input, if necessary, before submission to the IUCN.

The 'desktop' technique can and should incorporate population level data when available. For some species, the information is presently being gathered by field botanists, but the process is deemed to be too time-consuming and resource-intensive to be a regular activity for botanical collecting expeditions. The lack of population data usually precludes the use of Criterion E, a quantitative analysis, for plant species. Although some statistical models based on the sighting rate of specimens have been developed (Roberts & Solow 2003, Solow 2005), these have not yet been generally accepted as the basis of a quantitative assessment. We believe that with only a small addition of time and effort it is possible to record data that are extremely relevant for conservation assessments, for example, local environmental conditions (climate, soil), status of local area (disturbed, pristine), quality of population (regenerating, few individuals) and estimates of population size. The development and deployment of electronic data-gathering devices and standardised forms of data input will undoubtedly aid this process. Since there are so few experts for most groups, particularly plants, and since these experts already face many demands on their time, it can be a much more effective and time-efficient approach to have assessments compiled by non-experts and then verified by experts — where these exist. We also argue that, if multiple assessments are compiled by the same individual, even a non-expert, there will be a greater degree of standardisation and uniformity in the application of the IUCN Categories and Criteria than there will between numerous species 'experts' unused to the assessment methodology. In our experience, experts appreciate the contribution of GIS scientists and more often revise their conservation rating in line with the assessment data they are provided with than dispute the data and remain with their original rating.

THE SAMPLED RED LIST INDEX — MEASURING TRENDS IN THE STATUS OF BIODIVERSITY

A recent development of the IUCN Red List has been the formulation of a Red List Index (Butchart et al. 2004), a single value representing the conservation status of multiple species at a certain point in time, which may be used to track relative changes in conservation status by re-assessing these same species at regular intervals. Originally applied to birds (Butchart et al. 2004, 2005), it is now being expanded to cover all major groups of organisms for which sufficient species can be assessed (Baillie et al. 2008); this effort is being co-ordinated through the efforts of the Indicators and Assessments Unit at the Zoological Society of London (ZSL). For those speciose groups, including plants, which cannot be assessed in their entirety, a randomly selected sample of species is to be assessed; hence, the index will be known as the Sampled Red List Index (SRLI). The SRLI has already been adopted by the CBD, endorsed by COP VIII in 2006, as one of the measures of the World Summit on Sustainable Development (WSSD) 2010 Target:

> Parties commit themselves to a more effective and coherent implementation of the three objectives of the Convention to achieve by 2010 a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on earth. (Decision VI/26; UNEP 2002b, www.cbd.int/decisions/cop6/?m=COP-06&id=7200&lg=0).

After the 2010 Target had been set it was realised that there was not yet actually a measure of the current rate of loss of biodiversity, so it was not possible to know if this was being reduced. The SRLI was therefore adopted as a measure of this target, since it is species based and directly records threats to species conservation as a part of the assessment process. The Living Planet Index (LPI) (Loh et al. 2005), which measures trends in population size over time, was also adopted as a measure of the current rate of loss of biodiversity. For the plant component of the SRLI, being co-ordinated by us at RBG Kew, 5 major taxa have been selected: bryophytes, pteridophytes, gymnosperms, monocots and dicots. Selected at random from complete species checklists for these taxa, 1500 species have been chosen for each major taxon, except in the case of gymnosperms of which <1500 species in total exist — in this case all gymnosperm species are being assessed. The decision to take 1500 species of each group was made following simulation modelling from the complete assessments of birds (almost 10 000 species) and amphibians (>5500 species); above 900 species there is a <5% chance that the value of the SRLI for a sample of 1500 species will be significantly different from that of a completely assessed taxon, regardless of the size of that taxon, and this sample is also robust with respect to distribution, higher taxon and ecology (Baillie et al. 2008). There is also a built-in redundancy to allow up to 40% of the species to be Data Deficient.

This gives a grand total of about 7000 plant species being assessed, which will be representative of plant diversity and distribution patterns as a whole. However, since plants are in general a diverse and not well-known group, most of which have never received a conservation assessment, this means that we are left with a sample of 7000 poorly known species, most of which have never received a conservation assessment. There simply are not enough taxonomic and regional experts familiar with each of the plant species in the SRLI sample to carry out expert-based conservation assessments on our behalf. So, in order to generate comparable assessments and provide the baseline data against which future changes in conservation status can be measured, the assessments of plant species for the SRLI are reliant on databases of georeferenced herbarium specimens. Moreover, the automated GIS methodology described here must be used to prioritise those species in need of full conservation assessments (threatened or near threatened), to de-prioritise those species for which a full assessment would not be time effective (LC), and to flag up those species for which there is currently insufficient knowledge (DD). Approximately 30% of species so far assessed have proven at first-pass to be DD, with another 38% falling into the category LC and 32% into either NT (12%) or one of the threatened categories (20%) (see Fig. 3).

Having compiled the specimen data and carried out the conservation assessment, these are then passed to relevant experts, if these exist, for their input and/or verification. This remains a time-consuming but essential stage in the assessment process. With expert opinion included, assessments can then be submitted to the IUCN as standard (new) Red List assessments. This brings into relief the obvious drawback to this approach: a lack of experts and of proper field data to fully ground-truth these assessments. What is ideally needed, and the goal that comprises our objective and principal focus beyond 2010, is an international net-

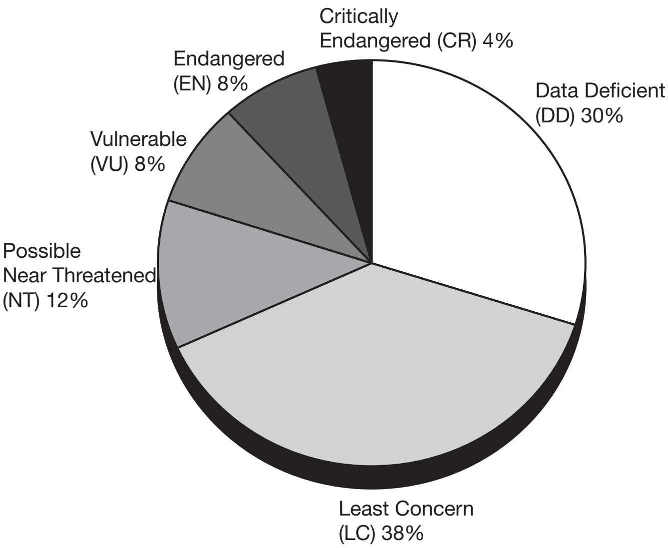


Fig. 3. Monocot threat status — results for preliminary assessments of ca. 600 species

work of field botanists actively going out and conducting field surveys of the species from the SRLI sample. In this way, as well as being able to apply Criteria B and D as we do now, we would also be able to test the conservation status of these species under Criteria A, C and possibly E. This will allow us to calculate a more balanced index. To this end we have developed a project website for the plant SRLI (http:// threatenedplants.myspecies.info/), where the summary information for each species can be accessed as it is gathered and collaborators will be able to input population survey data. As the project continues to develop we hope to add species pages and identification tools to aid these field surveys.

It might be argued that the SRLI approach is too coarse to reflect small changes in the conservation status of biodiversity, since large changes are needed to cause a change in the IUCN rating for an individual species and hence changes in the value of the index (Butchart et al. 2004). While this is a valid criticism, the simultaneous adoption and development of the LPI should mean that small changes in population sizes will also be noticed here. Ultimately, if accurate population data can also be gathered for the species in the SRLI sample, we will be able to carry out more accurate conservation assessments as well as base a plant LPI on the same set of species, to produce an LPI more representative of global patterns of biodiversity than is currently the case (Loh et al. 2005). Another criticism of the SRLI is that it is open to manipulation through conservation measures aimed specifically at those species in the sample: if those appear to be stable or their status is improving then this is reflected in a stable or improving index, even if other species are generally in decline. However, with an overall sample of many 1000s of species worldwide (Baillie et al. 2008) and detailed knowledge of the range and locations of each species, this knowledge base effectively spans most of the globe, and any conservation measures focused on the habitats or regions in which particular SRLI species are found will also have an additional benefit for those sympatric species not included in the index. Also, the sample size of 1500 was only recommended as a minimum requirement, so it is possible that in time more species would be included for each group in the SRLI.

As we continue to grind through our sample of almost 7000 species, for the first time there will be a representative sample of plants that have been fully assessed and documented in the Red List. This will be the baseline from which to compare post-2010 changes. This will tell us the percentage of plants we expect to be threatened, where the areas of greatest threat are, and what the threatening processes are. It will be the first scientifically defensible assessment of the current status of global plant diversity.

Acknowledgements. Work towards the Sampled Red List Index for Plants has been funded by the Department for Environment, Food and Rural Affairs, the Esmee Fairbairn Foundation, Rio Tinto plc and the Charles Wolfson Charitable Trust.

LITERATURE CITED

Baillie JEM, Collen B, Amin R, Akçakaya HR and others (2008) Toward monitoring global biodiversity. Conserv Lett 1:18–26

Bartholomé E, Belward AS (2005) GLC2000: a new approach to global land cover mapping from Earth observation data. Int J Remote Sens 26:1959–1977

Bomhard B, Richardson DM, Donaldson JS, Hughes GO and others (2005) Potential impacts of future land use and climate change on the Red List status of the Proteaceae in the Cape Floristic Region, South Africa. Glob Change Biol 11:1452–1468

Bramwell D (2002) How many plant species are there? Plant Talk 28:32–34

Buchanan GM, Butchart SHM, Dutson G, Pilgrim JD, Steininger MK, Bishop DK, Mayaux P (2008) Using remote sensing to inform conservation status assessment: estimates of recent deforestation rates on New Britain and the impacts upon endemic birds. Biol Conserv 141:56–56

Burgman MA, Grimson RC, Ferson S (1995) Inferring threat from scientific collections. Conserv Biol 9:923–928

Butchart SHM, Stattersfield AJ, Bennun LA, Shutes SM and others (2004) Measuring global trends in the status of biodiversity: Red List indices for birds. PLoS Biol 2:e383

Butchart SHM, Stattersfield AJ, Baillie JEM, Bennun LA and others (2005) Using Red List indices to measure progress towards the 2010 target and beyond. Philos Trans R Soc Lond B 360:359–372

Callmander MW, Schatz GE, Lowry PP II (2005) IUCN Red List assessment and the Global Strategy for Plant Conservation: taxonomists must act now. Taxon 54:1047–1050

Callmander MW, Schatz GE, Lowry PP II, Laivao MO and others (2007) Identification of priority areas for plant conservation in Madagascar using Red List criteria: rare and threatened Pandanaceae indicate sites in need of protection. Oryx 41:168–176

Chapman AD, Wieczorek J (2006) Guide to best practices for georeferencing. Global Biodiversity Information Facility, Copenhagen

Davis AP, Govaerts R, Bridson DM, Stoffelen P (2006) An annotated taxonomic conspectus of the genus *Coffea* (Rubiaceae). Bot J Linn Soc 152:465–512

Farjon A (2005) A monograph of Cupressaceae and Sciadopitys. Royal Botanic Gardens, Kew

Farjon A, Bachman S, Gardner M, Luscombe D, Reynolds C, Thomas P (2006) Conservation assessments of data deficient (DD) conifers, using herbarium and GIS data. Royal Botanic Gardens, Kew

Fitter R, Fitter M (eds) (1987) The road to extinction. IUCN, Gland

Frodin DG (2001) Guide to standard floras of the world: an annotated, geographically arranged systematic bibliography of the principal floras, enumerations, checklists and chorological atlases of different areas. Cambridge University Press, Cambridge

Govaerts R (2001) How many species of seed plants are there? Taxon 50:1085–1090

Govaerts R (2003) How many species of seed plants are there? A response. Taxon 52:583–584

Graham CH, Ferrier S, Huettman F, Moritz C, Peterson AT (2004) New developments in museum-based informatics and applications in biodiversity analysis. Trends Ecol Evol 19:497–503

Guralnick RP, Wieczorek J, Beaman R, Hijmans RJ, the BioGeomancer Working Group (2006) BioGeomancer: automated georeferencing to map the world's biodiversity data. PLoS Biol 4:e381

Hawthorne WD (2001) Forest conservation in Ghana: forestry, dragons, genetic heat. In: Weber W, White LJ, Vedder A, Naughton-Treves L (eds) African rain forest ecology and conservation: an interdisciplinary perspective. Yale University Press, New Haven, CT

Hitchmough R (comp.) (2002) New Zealand threat classification system lists — 2002. Threatened Species Occasional Publication 23, Department of Conservation, Welllington

IUCN (International Union for Conservation of Nature) (2001) IUCN Red List categories and criteria, Version 3.1. IUCN-SSC, Gland. Also available at: www.iucnredlist.org/static/categories_criteria_3_1

IUCN (International Union for Conservation of Nature) (2006) Guidelines for using the IUCN Red List categories and criteria, Version 6.2. Prepared by the Standards and Petitions Working Group of the IUCN SSC Biodiversity Assessments Sub-Committee in December 2006. www.iucnredlist.org/documents/redlist_guidelines_v1223290226.pdf

Loh J, Green RE, Ricketts T, Lamoreux J, Jenkins M, Kapos V, Randers J (2005) The Living Planet Index: using species population time series to track trends in biodiversity. Philos Trans R Soc Lond B 360:289–295

Miller BP, Enright NJ, Lamont BB (2007) Record error and range contraction, real and imagined, in the restricted shrub *Banksia hookeriana* in south-western Australia. Divers Distrib 13:406–417

Nic Lughadha E, Baillie J, Barthlott W, Brummitt NA and others (2005) Measuring the fate of plant diversity: towards a foundation for future monitoring and opportunities for urgent action. Philos Trans R Soc Lond B Biol Sci 360:359–372

Oldfield SF, Lusty C, Mackinven A (1998) The World List of threatened trees. World Conservation Press, Cambridge

Paton AJ, Brummitt NA, Govaerts R, Harman K, Hinchcliffe S, Allkin R, Nic Lughadha EM (2008) A working list of all known plant species—progress and prospects towards Target 1 of the Global Strategy for Plant Conservation. Taxon 57:1–10

Peterson AT, Stockwell DRB, Kluza DA (2002) Distributional prediction based on ecological niche modeling of primary occurrence data. In: Scott MJ, Heglund PJ, Morrison M, Haufler JB, Raphael MG, Wall WA, Samson FB (eds) Predicting species occurrences: issues of scale and accuracy. Island Press, Washington, DC, p 617–623

Pitman NCA, Jorgensen PM (2002) Estimating the size of the world's threatened flora. Science 298:989

Ponder WF, Carter GA, Flemons P, Chapman RR (2001) Evaluation of museum collection data for use in biodiversity assessment. Conserv Biol 15:648–657

Rapoport E (1982) Areography: geographical strategies of species. Pergamon Press, New York

Rico Arce ML, Bachman S (2006) A taxonomic revision of *Acaciella* (Leguminosae, Mimosoideae). An Jard Bot Madr 1979 63:189–244

Roberts DL, Solow AR (2003) Flightless birds — When did the dodo become extinct? Nature 426:245

Roberts DL, Moat J, McInerny G (2004) What have herbaria ever done for us? The role of herbaria in conservation assessments. Selbyana 25:299–303

Rodrigues ASL, Pilgrim JD, Lamoreux JF, Hoffmann M, Brooks TM (2006) The value of the IUCN Red List for conservation. Trends Ecol Evol 21:71–76

Schatz G, Birkinshaw C, Lowry PP II, Randriantafika F, Ratovoson F (2000) The endemic plant families of Madagascar project: integrating taxonomy and conservation. In: Lourenço WR, Goodman SM (eds) Diversité et Endemisme à Madagascar. Mem Soc Biogeogr, Paris, p 11–24

Sérgio C, Figueira R, Draper D, Menezes R, Sousa JA (2007) Modelling bryophyte distribution based on ecological information for extent of occurrence assessment. Biol Conserv 135:341–351

Solow AR (2005) Inferring extinction from a sighting record. Math Biosci 195:47–55

Stevens PF (2008) Angiosperm phylogeny website, Version 7. www.mobot.org/MOBOT/research/APweb/ (accessed 24 January 2008)

UNEP (United Nations Environment Programme) (2002a) Global Strategy for Plant Conservation. COP Decision VI/9, CBD Secretariat, Montreal. www.cdb.int/decisions/cop6/?m=COP-06&id=7183&lg=0

UNEP (United Nations Environment Programme) (2002b) Strategic Plan for the Convention on Biological Diversity. COP Decision VI/26, CBD Secretariat, Montreal. www.cbd.int/decisions/cop6/?m=COP-06&id=7200&lg=0

Ungricht S (2004) How many plant species are there? And how many are threatened with extinction? Endemic species in global biodiversity and conservation assessments. Taxon 53:481–484

Utteridge T, Nagamasu H, Teo SP, White LC, Gasson P (2005) *Sleumeria* (Icacinaceae): a new genus from northern Borneo. Syst Bot 30:635–643

Walter K, Gillett H (eds) (1998) 1997 IUCN Red List of threatened plants. IUCN, Cambridge

Willis F, Moat J, Paton A (2003) Defining a role for herbarium data in Red List assessments: a case study of *Plectranthus* from eastern and southern tropical Africa. Biodivers Conserv 12:1537–1552

Editorial responsibility: Matthew Godfrey, Beaufort, North Carolina, USA

Submitted: June 2, 2008; Accepted: August 26, 2008
Proofs received from author(s): November 12, 2008

Diversity and Distributions, (Diversity Distrib.) (2017) **23**, 435–447

BIODIVERSITY RESEARCH

Using coarse-scale species distribution data to predict extinction risk in plants

Sarah E. Darrah[1]*, Lucie M. Bland[2], Steven P. Bachman[3,4], Colin P. Clubbe[3] and Anna Trias-Blasi[3]

[1]*United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), Cambridge CB3 0DL, UK,* [2]*School of BioSciences, The University of Melbourne, Parkville, VIC 3010, Australia,* [3]*Royal Botanic Gardens, Kew, Richmond, Surrey TW9 3AB, UK,* [4]*School of Geography, University of Nottingham, Nottingham NG7 2RD, UK*

*Correspondence: Sarah Darrah, United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), Cambridge CB3 0DL, UK.
E-mail: sarah.darrah@unep-wcmc.org

ABSTRACT

Aim Less than 6% of the worlds described plant species have been assessed on the IUCN Red List, leaving many species invisible to conservation prioritization. Large-scale Red List assessment of plant species is a challenge, as most species' ranges have only been resolved to a coarse scale. As geographic distribution is a key assessment criterion on the IUCN Red List, we evaluate the use of coarse-scale distribution data in predictive models to assess the global scale and drivers of extinction risk in an economically important plant group, the bulbous monocotyledons.

Location Global.

Methods Using coarse-scale species distribution data, we train a machine learning model on biological and environmental variables for 148 species assessed on the IUCN Red List in order to identify correlates of extinction risk. We predict the extinction risk of 6439 'bulbous monocot' species with the best of 13 models and map our predictions to identify potential hotspots of threat.

Results Our model achieved 91% classification accuracy, with 88% of threatened species and 93% of non-threatened species accurately predicted. The model predicted 35% of bulbous monocots presently 'Not Evaluated' under IUCN criteria to be threatened and human impacts were a key correlate of threat. Spatial analysis identified some hotspots of threat where no bulbous monocots are yet on the IUCN Red List, for example central Chile.

Main conclusions This is the first time a machine learning model has been used to determine extinction risk at a global scale in a species-rich plant group. As coarse-scale distribution data exist for many plant groups, our methods can be replicated to provide extinction risk predictions across the plant kingdom. Our approach can be used as a low-cost prioritization tool for targeting field-based assessments.

Keywords

bulbous monocotyledons, extinction risk, IUCN Red List, machine learning, plants, predictive modelling.

INTRODUCTION

Plant diversity across the globe is at risk from anthropogenic changes such as habitat loss, degradation and overexploitation (Corlett, 2016), yet the extent and drivers of species extinction, as well as the strategies to counteract them, remain poorly known. These challenges are compounded by the sheer size of the plant kingdom, with 350,699 accepted species names on The Plant List to date (The Plant List, 2013). The size of the group, compared to comprehensively assessed vertebrate groups like birds (10,425 species) and mammals (5513 species), is one of the reasons plants are underrepresented on the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species™. The IUCN Red List contains 21,898 plant assessments (IUCN, 2016) which equates to 6% of described plants, although as much as a third of these assessments are considered out of date as they are either more than 10 years old or

DOI: 10.1111/ddi.12532
http://wileyonlinelibrary.com/journal/ddi

use an earlier version of the criteria (IUCN Standards And Petitions Subcommittee, 2014). Of those plants assessed, 53% are listed as threatened (Critically Endangered, Endangered, Vulnerable) (IUCN, 2016), but risk is likely to be overestimated as assessment efforts have been preferentially directed towards the most threatened species and areas (Rodrigues *et al.*, 2006).

To better understand the global threat status of plants, the IUCN Sampled Red List Index (SRLI) for plants assessed the status of a random sample of plant species to give a representative view of plant extinction risk globally (Brummitt *et al.*, 2015). The results indicated a much lower proportion of species are threatened (21%) compared to species published on the current version of the Red List (53%), which nevertheless implies that as many as 74,000–84,000 plants could be at risk. Although Red List assessments in isolation are not an appropriate device for conservation prioritization (Possingham *et al.*, 2002), they are an important component for a range of prioritization and funding schemes such as Mohamed Bin Zayed Conservation Trust (www.speciesconservation.org), Save our Species (SOS; www.sospecies.org) and the Critical Ecosystem Partnership Fund (CEPF; www.cepf.net). The absence of a strategic prioritization system for plant Red List assessments means that many species could be missing out on conservation funding (Bland *et al.*, 2015b).

Given the large number of plants remaining to be assessed on the IUCN Red List, devising approaches to facilitate their assessment or to include them in conservation prioritization without formal assessments are of the highest priority (Callmander *et al.*, 2005; Royal Botanic Gardens, Kew, 2010). We therefore must refine our understanding of what factors contribute to high extinction risk and which plant species are likely to be at highest risk (Duffy *et al.*, 2009; Brummitt *et al.*, 2015). Predictive modelling of extinction risk is a widely used tool to quantify threat levels across taxa and prioritize conservation research (Purvis *et al.*, 2000; Cardillo *et al.*, 2008; Di Marco *et al.*, 2014; Jetz & Freckleton, 2015). Machine learning models such as random forests are popular due to their ability to find patterns in large and complex datasets (Di Marco *et al.*, 2014; Bland *et al.*, 2015a), and there is clear potential to apply these models to plants (Duffy *et al.*, 2009). Existing studies of extinction risk in plants focus on national or regional scales, for example Amazonian plants (Feeley & Silman, 2009). Global extinction risk studies are more challenging as they rely on the availability of systematic, global data for the large majority of species under study. In particular, lack of high-resolution, high-quality occurrence data for most plant species presents limitations in scaling up the previous models (Bland *et al.*, 2015b).

The World Checklist of Selected Plant Families (WCSP) is a coarse-scale dataset of species presence according to a hierarchical geographic coding system derived from the Taxonomic Databases Working Group (TDWG; Brummitt *et al.*, 2001). Data are complete for a large number of plant families and comprehensive for broad taxonomic groups such as the monocotyledons (WCSP, 2014). The coding at level one is continental, level two is regional and level three is broadly equivalent to small countries and islands (Brummitt *et al.*, 2001). This coarse-scale geographic coding of plant distributions has not yet been explored as a predictive tool for extinction risk assessment. In this paper, we quantify the effect of high-quality range data on variable importance by comparing models using both coarse-scale and fine-scale species distribution data.

Modelling extinction risk relies on identifying appropriate variables which correlate with extinction risk in species of known conservation status. Correlates broadly fall into intrinsic (life history traits, e.g. habit and dispersal mode, and ecological traits, e.g. range size) and extrinsic variables (environmental and anthropogenic) and the most informative models combine both types of data (e.g. Davies *et al.*, 2011). For vertebrates, studies often focus on intrinsic traits such as body mass, fecundity and niche characteristics (Purvis *et al.*, 2005; Di Marco *et al.*, 2014). Intrinsic correlates of extinction risk are less researched for plants at higher taxonomic levels, including pollination syndrome, height, habit, sexual system and dispersal mode (e.g. Laliberté, 2016), but there have been some recent advancements in understanding plant functional traits (e.g. Bullock *et al.*, 2002; Pywell *et al.*, 2003; Cornwell *et al.*, 2014; and Diaz *et al.*, 2016). Extrinsic variables are known to be good predictors of extinction risk (Lee & Jetz, 2010; Murray *et al.*, 2014; Di Marco & Santini, 2015). The SRLI for plants found human impacts to be the greatest cause of threat to plants, particularly the conversion of natural habitats to agricultural land (Brummitt *et al.*, 2008, 2015) and global data on human threats are increasingly available for use in models (e.g. CIESIN & CIAT, 2005; Hansen *et al.*, 2013).

We bridge this gap by focusing on bulbous monocotyledons, a relatively well-known plant group. Bulbous monocot is an informal term that refers to all Monocotyledons in the orders Liliales and Asparagales with a geophytic life-form and petaloid flowers (excluding Orchidaceae) (A. Trias-Blasi, Royal Botanic Gardens, Kew, London, pers. comm.). There are approximately 7000 bulbous monocot species in eight different plant families (Amaryllidaceae, Asparagaceae (subfamilies Scilloideae and Brodiaeoideae), Colchicaceae, Iridaceae, Ixioliriaceae, Liliaceae, Melanthiaceae and Tecophilaeaceae) (WCSP, 2014). Many bulbous monocot taxa are economically important due to their horticultural, medicinal and nutritional value (Marshall, 1993). Bulbous monocots, such as snowdrops, have been greatly affected by illegal collecting activities linked to international trade, which has led to their inclusion on the checklist of the Convention on Trade in Endangered Species of Wild Fauna and Flora (CITES) (Davis, 1999; Yüzbaşioğlu, 2008; Newton *et al.*, 2014). Small range size, extractive activities and habitat loss from agricultural development, grazing, urban expansion, road building and tourism in littoral/montane sites also threaten species survival across global ranges and are likely to be good predictors of extinction risk (Özhatay *et al.*, 2013; IUCN, 2014). To date, the extinction risk of only c. 2% (148 species) of bulbous monocots has been assessed against the IUCN Red List criteria (IUCN, 2015), so the majority of species are categorized as Not Evaluated (NE). As bulbous monocots have complete geographic range data on the WCSP (WCSP, 2014), they are an excellent case study to test the applicability of extinction risk models, not only for monocotyledons but also for plants in general.

Using bulbous monocots as a study group, we build models to discriminate threatened and non-threatened species based on species-level data. Using species assessments from the IUCN Red List and SRLI as a training set, we build models to predict the threat status of bulbous monocots that are yet to be assessed. Our aims are to: (1) test the utility of coarse-scale distribution data in extinction risk models compared to fine-scale data; (2) identify correlates of extinction risk in bulbous monocots; and (3) predict levels of extinction risk in non-assessed species. If models perform well using coarse-scale distribution data, they will provide a much needed tool to understand the drivers of threat in bulbous monocots and to prioritize conservation efforts at a global scale. It could also provide opportunities for application to other plant groups and be up scaled to the whole plant kingdom.

METHODS

Predicting species extinction risk and prioritizing conservation actions can be achieved in five steps: data collection, model validation, predictive modelling, prioritization and review of the process (Fig. 1).

Distribution data

We obtained a list of all bulbous monocot species and associated Taxonomic Databases Working Group (TDWG) level 3 distributions from the World Checklist of Selected Plant Families (WCSP, 2014). We partitioned the list into two groups: *assessed* and *non-assessed*, based on IUCN Red List and Sampled Red List Index assessments. Species assessed as Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT) and Least Concern (LC) formed the assessed group, comprising 148 species, and Data Deficient (DD) and Not Evaluated (NE) species formed the non-assessed group, comprising 6439 species (Table 1). We excluded species classified as Extinct (EX) or Extinct in the Wild (EW), five species with missing distribution data, and families with either no assessed species (Ixioliriaceae and Tecophilaeaceae) or fewer than eight assessed species (Melanthiaceae).

Table 1 IUCN Red List risk categories of bulbous monocotyledon species used in the model.

IUCN Red list category	Number of species
Critically endangered (CR)	7
Endangered (EN)	24
Vulnerable (VU)	28
Near threatened (NT)	6
Least concern (LC)	83
Total assessed	**148**
Data deficient (DD)	56
Not evaluated (NE)	6383
Total non-assessed	**6439**
Total species	**6587**

Figure 1 Framework of steps to predict species extinction risk and prioritize conservation action. This analysis starts with the first three steps: data collection, model validation and modelling predicted extinction risk. To ensure effective conservation on the ground, we recommend the results of these steps inform conservation prioritization and that the process is reviewed and refined as data sources and model techniques are improved.

Correlates of extinction risk

We selected predictor variables based on expected correlates of extinction risk and data availability. We used seven variables grouped into taxonomy, geographic distribution, human impacts and conservation action (Table 2).

We used the count of TDWG level 3 regions (representing small countries or islands) within a species range as an indicator of range size, with a score of one representing endemic species. We also included an indicator of isolation, measured as percentage of islands across a species distribution. Data on life history traits are sparse and incomplete across plant groups. For the majority of plant groups, only life-form data (habit) are consistently available, which are redundant for this analysis as all bulbous monocots are by definition geophytes. To indicate differences in life history traits that could mediate extinction risk we used taxonomic family to account for shared evolutionary history. We use taxonomy as a surrogate for phylogeny due to data availability. Although there are some phylogenetic studies of bulbous monocot families (Seberg *et al.*, 2012; Chen *et al.*, 2013; García *et al.*, 2014), it is currently difficult to incorporate phylogenetic relatedness in machine learning when there is no consolidated phylogeny at the group level. In addition, whilst phylogeny can be informative, it is currently not possible to include phylogeny in a computationally appropriate way in machine learning models, and data on life history traits is preferable for both predictive power and interpretability (Bland *et al.*, 2015a). Within each TDWG level 3 region, we queried GIS layers of human impacts and conservation action to calculate average values across all the regions within each species range. Human impact variables included the following: Human Footprint Index (WCS, 2005), human population density (CIESIN & CIAT, 2005) and global forest loss (Hansen *et al.*, 2013). We used forest loss as a surrogate for habitat loss, as it has been shown to have adverse effects on a diverse range of habitats, for example grassland and savannas (Boakes *et al.*, 2010). We measured conservation action as the percentage area formally protected by intersecting TDWG level 3 regions with protected area polygons (IUCN & UNEP-WCMC, 2014). We then calculated average percentage area across each species distribution in an equal area cylindrical projection.

As TDWG level 3 regions are not equal in terms of area coverage, each region was normalized by the area of the region before averaging across the species range. We base predictions on current levels of threat and do not attempt to predict future risk levels under different scenarios, so climate change variables were not included.

Extinction risk models and spatial analysis

We normalized predictor variables and split the data to create a training set of assessed species and a prediction set of non-assessed species. Multiple methods are available to model and predict extinction risk (Di Marco *et al.*, 2014; Bland *et al.*, 2015a; Luiz *et al.*, 2016). Phylogenetic least squares is a popular method to explain extinction risk (Purvis *et al.*, 2000; Cardillo *et al.*, 2008), but is unsuitable for groups with no consolidated global phylogeny and shows

Table 2 Summary of predictor variables used in the model and data sources. Variables are organized in different groups: extinction risk, taxonomy, geographic distribution and human impacts.

Variable group	Variable	Description	Reference
Extinction risk	Threat status – Red List assessed	Species assessed through IUCN Red List. Threat categories: CR, EN, CN, LC, NT, DD. Assessment dates range from 2003 to 2013	IUCN (2014)
	Threat status – SRLI assessed	Species assessed in Sampled Red List Index project with IUCN threat categories	Royal Botanic Gardens, Kew (2010)
Taxonomy	Plant family	Bulbous monocotyledon plant family group	WCSP (2014)
Geographic distribution	Range size	Number of Taxonomic Databases Working Group level 3 regions across a species range	
	Isolation	Percentage islands across species range	
Human impacts	Human Footprint Index (1995–2004)	Raster 1-km resolution dataset created from nine global data layers covering human population pressure, human land use, infrastructure and human access	WCS (2005)
	Human population density (2000)	Raster 2.5-arc minute resolution dataset, each grid cell represents population density	CIESIN & CIAT (2005)
	Global forest loss (2000–2012)	Raster 30-m-resolution dataset, each grid cell represents forest loss encoded as 1 (loss) and 0 (no loss)	Hansen *et al.* (2013)
Conservation action	% Area protected	Percentage area covered by protected areas within species range. Calculated by intersecting World Database on Protected Areas with Taxonomic Databases Working Group level 3 regions in each species range	IUCN & UNEP-WCMC (2014)

limited predictive power (Bland, 2015a). Because of the absence of consolidated global phylogenies for bulbous monocots (but see species available on Open Tree of Life) and our focus on predicting the status of non-assessed species, we use the machine learning model 'random forests', an ensemble of decision trees that repeatedly split predictors into increasingly homogenous groups. Random forests show high predictive power in extinction risk analyses compared to other machine learning tools (Bland, 2015a). These models were trained with assessed species and associated predictor variables to model the probability of threat in non-assessed species (Kuhn, 2008; R Core Development Team, 2014). Within the training set, we categorized threat status as 'threatened' (Critically Endangered, Endangered, Vulnerable) and 'non-threatened' (Near Threatened and Least Concern) due to difficulty in discriminating five imbalanced categories (e.g. 83 Least Concern and 7 Critically Endangered species; see Appendix S1 in Supporting Information, Table S1.2) (Hand, 2012; Luiz *et al.*, 2016). To test for variation in model results due to sampling bias, we first ran models separately for IUCN Red List and SRLI species. To maximize sample size, we then grouped all species to test likely correlates of extinction risk.

To reliably predict the status of non-assessed and assessed species, it is imperative to assess model performance, that is, the ability of the model to accurately predict the extinction risk of species of known conservation status. We set model parameters to run 500 trees to prevent overfitting and assessed predictive accuracy using 10-fold cross-validation repeated five times on the training set. We used area under the receiver operating characteristic curve (AUC) as the most appropriate measure of model performance, as it assigns equal weight to both sensitivity and specificity whilst accounting for imbalanced threat categories in our training set (see Appendix S1, Table S1.2). We selected the optimal probability threshold by maximizing the Youden Index (sensitivity + specificity − 1; Perkins & Schisterman, 2006). We then undertook variable selection to understand if drivers identified by the SRLI project are also correlates of extinction risk in bulbous monocots, which were underrepresented in the original assessment. We measured variable importance with the mean decrease in Gini Index; a large decrease indicates high levels of statistical dispersion (Breiman *et al.*, 1984).

Some variables are likely to correlate with extinction risk at subnational and local levels. Therefore, we also tested models based on fine-scale range size data, using a subset of assessed species for which these data were available. We used IUCN polygon range maps for IUCN Red List species. Because range maps are not available for SRLI species, we constructed maps based on occurrence points. We buffered each occurrence point with a 10-km radius and created a minimum convex polygon around those points. The 10-km radius was chosen to represent the area over which a population is expected to experience threats. We calculated range area in km² and extracted mean values of variables across species ranges. These models quantify the effect of high-quality range data on variable importance, but cannot be used to predict extinction risk in non-assessed species for which range size data are not available.

We predicted the status of 6439 species with the best model and mapped the spatial distribution of predicted threatened species to identify potential hotspots of threat. These maps were compared with the distribution of threatened bulbous monocot species that are currently on the IUCN Red List to identify priority areas where predicted threat levels are high, but few or no species have been assessed. Such gaps can be used to prioritize future conservation assessments.

RESULTS

Assessing the ability of our model to predict extinction risk in species of known conservation status

The model results demonstrate good predictive performance with a high area under the receiver operating characteristic curve (AUC = 0.98) indicating a good fit of the model to the data (Pearce & Ferrier, 2000) and high classification accuracy (91% of species were correctly classified during cross-validation). The model accurately classified 88% of threatened species (sensitivity) and 93% of non-threatened species (specificity; Table 3).

There was good discrimination between the threatened and non-threatened classes with particularly strong discrimination between Critically Endangered species and non-threatened species (Near Threatened and Least Concern) (Fig. 2). All Critically Endangered species were correctly predicted, indicating strong predictive capacity for species with high extinction risk. Near Threatened species, which are on the threshold between threatened and non-threatened, had the lowest proportion correctly classified. Identification of individual species misclassified revealed that some species (almost all of which are endemic to a single TDWG level 3 unit) were consistently misclassified across models. We found

Table 3 Performance statistics of random forest model for assessed bulbous monocotyledons.

Parameter	Value
No. species	148
No. variables	7
Accuracy	0.91
95% CI	0.86, 0.95
Sensitivity	0.88
Specificity	0.93
AUC	0.98
Threshold probability	0.46
Youden Index	0.82
Kappa	0.82
% Predicted threatened	35

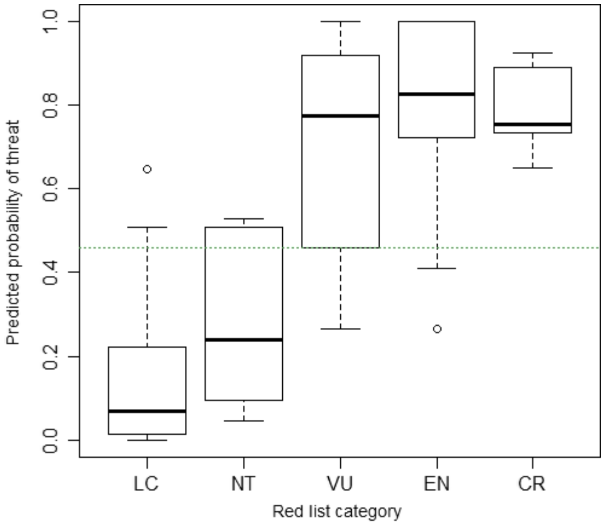


Figure 2 Predicted threat probability for assessed bulbous monocotyledon species by IUCN Red List category (n = 148). Dotted line indicates the modelled threshold probability between threatened and non-threatened categories of 0.46. Boxplot shows median, first and third quartile and 95% confidence internal of the median.

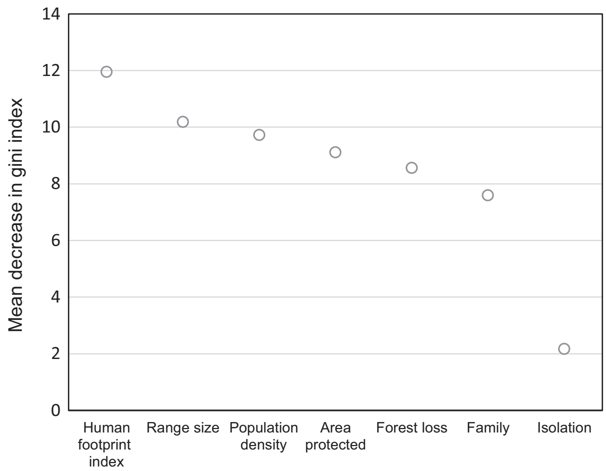


Figure 3 Relative importance of predictor variables ranked according to mean decrease in Gini Index. A large decrease indicates a high level of statistical dispersion.

that classification accuracy for endemic species was lower than the average for the model (86% compared to 91%). Of particular note is the higher misclassification rate of species endemic to Cape Provinces (5 of 26 endemics were misclassified, 81% accuracy), including the two outliers in Fig. 2 (*Crinum variable* – misclassified as threatened and *Romulea aquatic* – misclassified as not threatened).

Identifying correlates of high extinction risk

Analysis of variable importance revealed that human impact variables (Human Footprint Index, human population density and forest loss) and the conservation action variable (percentage area under formal protection) were strong correlates of extinction risk (Fig. 3). The surrogate for range size calculated from TDWG regions was also important with the second greatest contribution to the predictive ability of the model. Plant family and isolation were not strong correlates of threat but still contributed to overall predictive performance, possibly because of interaction effects with other variables.

The model based on fine-scale range data derived from IUCN polygons and SRLI point data again showed good discrimination between threatened and non-threatened classes (see Appendix S1, Table S1.4), with all but one species correctly classified. Species range size had a much larger contribution to model performance when we used fine-scale range data than in models using TDWG distributions (see Appendix S1, Fig. S1.2).

Predicting the status of non-assessed species

When we applied the model with the highest area under the receiver operating characteristic curve (AUC) to predict extinction risk in bulbous monocots, we found that 35% (2237 of 6439) of species were predicted to be threatened (see Appendix S2, Table S2). Sequential removal of variables with the lowest contribution to the model reduced model performance, so the final model contained all seven predictor variables (Table 2). Running a separate model on IUCN Red List species resulted in reduced model performance (78% of species correctly classified; see Appendix S1, Table S1.3), whilst the model on SRLI species resulted in high model performance (91% correctly classified) but is based on a sample of only 38 assessed species. There was no substantial difference in variable importance between the two models based on IUCN Red List and SRLI species, so all species were pooled to fit the final model.

Analysis of model predictions by geographic region reveals a strong geographic clustering of extinction risk predictions. ‘Hotspots’ of global threat include the following: Turkey and Cape Provinces (> 153 species predicted to be threatened), Iran, central Chile, Greece, Spain, Lebanon, Syria, Northern Provinces and Transcaucasus (> 90 species predicted to be threatened; Fig. 4c). Regions with a high density of species assessed as threatened were reflected with a high density of predicted threatened species, for example, in Greece, Spain and Cape Provinces. In contrast, some regions, for example Ecuador, with a high density of assessed threatened species were not predicted to have a high density of threatened species (Fig. 4b,c).

DISCUSSION

In light of global environmental change, it is paramount to identify which species are at high risk of extinction and to diagnose drivers of risk in order to reverse biodiversity declines. Acquiring this information is particularly challenging for species-rich and poorly studied groups such as plants (Brummitt *et al.*, 2015). Bulbous monocots are a good study group as they are a relatively well-known group of plants

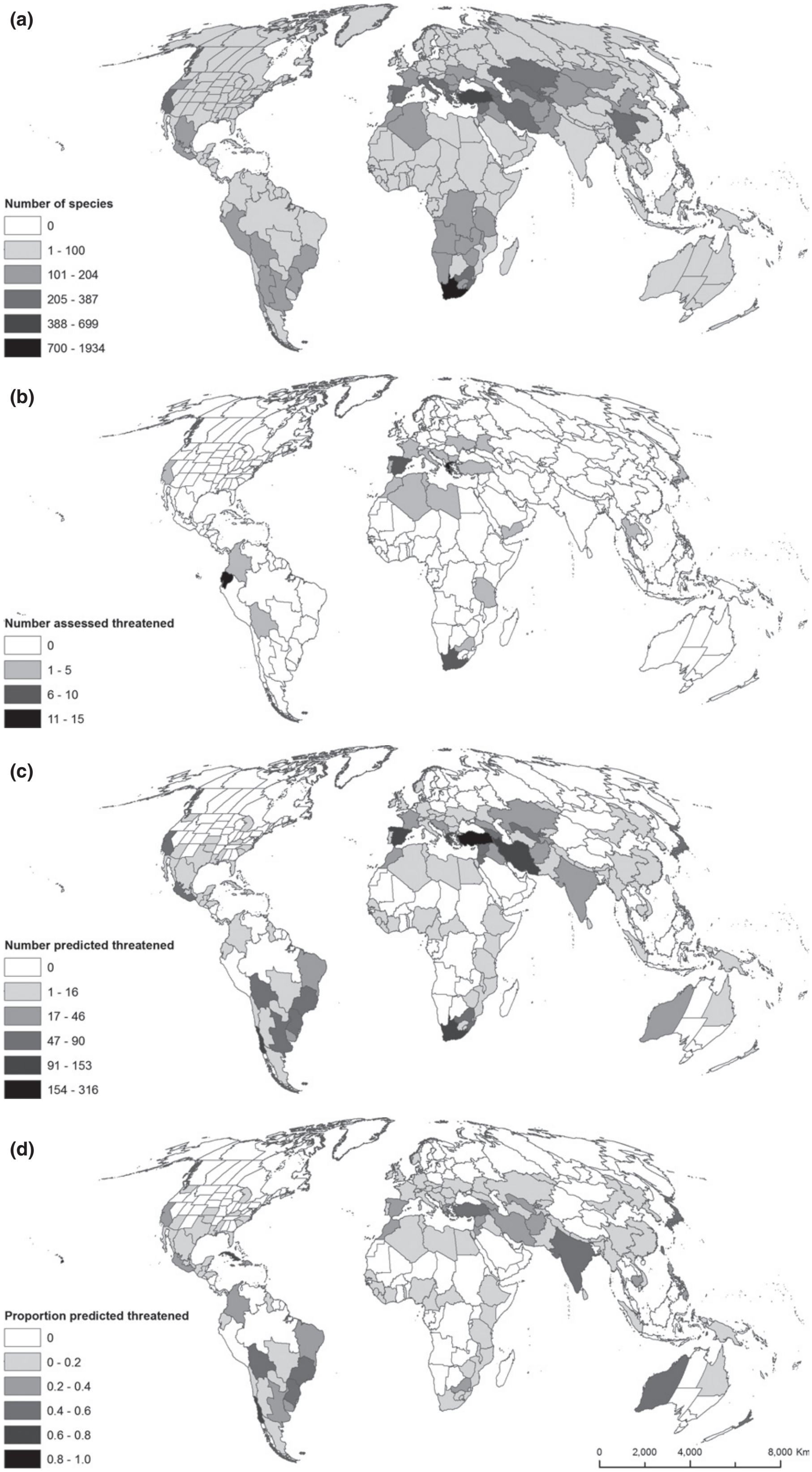


Figure 4 Global geographic distribution of bulbous monocotyledon species occurrence: (a) species richness, (b) number of assessed threatened species (Sampled Red List Index and IUCN Red List; Royal Botanic Gardens, Kew, 2010; IUCN, 2014), (c) predicted number of threatened species, (d) predicted proportion of threatened species. All maps are based on Taxonomic Databases Working Group level 3 regions in Mollweide projection.

comprising horticulturally important plants which are widely traded (Davis, 1999; Yüzbaşioğlu, 2008; Newton *et al.*, 2014), and threatened in the wild (Özhatay *et al.*, 2013; IUCN, 2014). We present the first global analysis of bulbous monocots, giving much needed indications of threat levels and correlates of risk across this economically important plant group. This information is crucial in order to prioritize geographic regions and individual species for future conservation interventions, including IUCN Red List assessments and trade controls.

IUCN Red List assessments and indices underpin a number of the Aichi Biodiversity Targets of the Strategic Plan for Biodiversity 2011–2020 as well as the cross-cutting Global Strategy for Plant Conservation. Achieving Target 2 of the Global Strategy for Plant Conservation 'an assessment of the conservation status of all known plant species, as far as possible, to guide conservation action' by 2020 will require rapid advances to increase the rate and reduce the high cost of species assessments (Baillie *et al.*, 2008; Juffe-Bignoli *et al.*, 2016). In addition, with limited funding there will undoubtedly be trade-offs between increasing the number of plant assessments and keeping current assessments up to date (Rondinini *et al.*, 2014). A recent review of progress in achieving the Global Strategy for Plant Conservation indicated that Target 2 is unlikely to be met by 2020 (Sharrock *et al.*, 2014), highlighting the urgent need for rapid and cost-effective assessments (Bland *et al.*, 2015b, 2016).

Our model predicts that 35% of non-assessed bulbous monocots are currently at risk of extinction, resulting in a potential 2254 additional threatened species to the 59 already assessed as threatened on the IUCN Red List (IUCN, 2015). This estimate is higher than the global average for plants based on the SRLI (20%) (Brummitt *et al.*, 2015). However, these predictions are much closer to extinction levels in another horticulturally important group, the cacti (Cactaceae), for which 31% of species are at risk (Goettsch *et al.*, 2015).

Coarse-scale global analyses can be used to predict hotspots of threat and systematically prioritize species assessments using local data (Smith *et al.*, 2009). In addition to predicting known hotspots of threat, for example Turkey and Cape Provinces, our model predicted hotspots where no bulbous monocot species have yet been assessed, for example central Chile (72% of species predicted to be threatened), and some hotspots where no species have yet been assessed as threatened, for example Iran, Lebanon and Syria (Fig. 4b, c). Many species-poor regions exhibit high levels of predicted extinction risk (Fig. 4a,c), for example, more than half of India's 50 species are predicted to be threatened, including 25 endemic species. On the other hand, some species-rich areas are predicted to have few or no threatened species, for example Namibia where none of its 204 species are predicted to be threatened. This global view can be used to prioritize international conservation efforts to target the most vulnerable regions, thereby increasing cost-effectiveness and demonstrating value for money.

The drivers of extinction risk in bulbous monocots have received limited research at the group level, yet trade in bulbs has been increasing (CITES Trade Database, 2016) and the value of international floriculture exports, including bulbs, increased from US \$8.5 billion in 2011 to US \$20.6 in 2013 (UN Comtrade, 2014). Our model highlights common patterns in the human impact and biological variables used to predict extinction risk. As also highlighted by other taxon-wide studies (Cardillo *et al.*, 2008; Murray *et al.*, 2014; Di Marco & Santini, 2015) and the SRLI project, human impacts were key in distinguishing between threatened and non-threatened species. The Human Footprint Index and population density were strong correlates of extinction risk (Fig. 3). This is likely due to close correlation with habitat degradation through urbanization, the second most common threat for bulbous monocots on the IUCN Red List (IUCN, 2014).

Range size was also an important correlate, reflecting the inherent role of range size in IUCN criteria (IUCN, 2001). The strongest effects were seen in species with narrow ranges (fewer than three Taxonomic Databases Working Group level 3 regions; see Appendix S1, Fig. S1.3a). The relationship between percentage area protected and likelihood of extinction is less clear, perhaps reflecting poor data coverage or because protected areas are not usually created and managed for plants. Whilst the World Database on Protected Areas is the best available global dataset for protected areas, it is compiled from the submission of national data and, as such, the data are incomplete and outdated for many countries (UNEP-WCMC, 2015). Issues of data coverage are particularly prevalent in Middle Eastern countries, for example Turkey, where bulbous monocot species richness is highest. Consistent with previous studies, plant family does not appear to be a good correlate of extinction risk (Fréville *et al.*, 2007). Isolation was also a poor correlate but the indicator could be strengthened if population data were collected more widely. Understanding how drivers of threat in bulbous monocots compare to plants as a whole is an important step in ensuring plant conservation strategies are suitable at the group level.

To be confident in predictions of extinction risk in non-assessed species, it is paramount to assess the capacity of the model to accurately predict risk in species of known conservation status. Our model showed high classification accuracy (91%) in line with extinction risk models for other taxa, for example 90% for mammals in Di Marco *et al.* (2014) and 95% for birds in Machado & Loyola (2013). However, the accuracy of our model in predicting threatened species (88% model sensitivity) is an improvement on previous models, for example 68% in Di Marco *et al.* (2014) and 24% in Machado & Loyola (2013). The ability to accurately identify threatened species is appropriate for conservation problems as it is more risk averse to predict species as threatened when they are not (false positives) than to predict species as not threatened when they are (false negatives). Model performance is particularly high for Critically Endangered species, whereas Near Threatened species had the lowest classification accuracy. This may reflect the lack of quantitative criteria to define the Near Threatened threshold (IUCN, 2001), meaning that the boundary for this category is more ‘fuzzy’ than for threatened categories.

Although model performance was good, poor data availability imposes limitations on the inferences we can make from the results (Table 4 shows limitations and recommendations). Model validation was based on a sample of 148 assessed species which were used to predict the extinction risk of 6439 non-assessed species. Jetz & Freckleton (2015) consider predictions to be sufficiently reliable when 60% of species have been assessed and are used to train predictions for non-assessed and/or Data Deficient species. To predict extinction risk in bulbous monocots through modelling alone, this would equate to random assessment of 3952 species before then predicting the remaining 40%. We therefore recommend first validating this approach using random samples at national and subnational levels, focusing on areas for which there is an abundance of plant information and assessments. For example, the South African National Biodiversity Institute (SANBI, 2014) has nationally assessed 1987 bulbous monocots and is a good candidate for further model validation. However, obtaining suitable re-assessment data to validate extinction risk models remains a challenge (Bland *et al.*, 2016) and such validation is in itself biased and may not estimate the true accuracy of the model (Hastie *et al.*, 2009).

Our model assumes the relationships between correlates and assessed species in the training set are transferrable to non-assessed species. This assumption is substantial considering the apparent bias towards threatened species assessments in IUCN Red List. Nevertheless, models run separately for IUCN Red List and randomly sampled SRLI species did not show substantial differences in variable importance. The most important predictor variables were indicators of habitat degradation, a non-species-specific threat, which the SRLI found to hold true across plant groups under random sampling (Brummitt *et al.*, 2015).

Most predictor variables used in the model show strong correlations with extinction risk; however, increasing the number and range of variables is likely to better capture variations in extinction risk globally. For example, forest loss data, mainly based on forest cover derived from satellite imagery, may not adequately represent the nuances of habitat degradation such as selective logging (Burovalova *et al.*, 2015). We recommend that land cover/land use data are included alongside forest loss in future models.

As our approach is restricted to systematic, globally available datasets, the range of species-specific threat data that could be included in the model was limited. Inclusion of such data, for example overharvesting of wild populations for trade, is likely to improve the accuracy of predictions yet are currently only available for a small number of species (see Table 1 in Smith *et al.*, 2011).

This study highlights that models based on coarse-scale species distribution data can provide rapid and low-cost options for preliminary assessments of extinction risk and conservation prioritization. As the Taxonomic Databases

Table 4 Key limitations and recommendations on the data and model used in the analysis.

Data category	Limitations	Recommendations
Data availability and quality		
Species assessments	Small training set – 148 species Possible inconsistency of application of the Near Threatened IUCN category	Increase sample size
Species-specific data	No species-specific predictor variables, for example phylogeny, trade data, population trends	Increase data collection efforts Use imputation methods, for example phylogenetic imputation when a phylogeny becomes available (Bruggeman *et al.*, 2009)
Species range data	Taxonomic Databases Working Group regions used as surrogates for species distributions, likely overestimating range size Coarse-scale range data may mask the effects of predictor variables acting at subnational levels	Match resolution of range size data to that of environmental and socioeconomic variables Investigate use of data aggregators e.g. GBIF as a source for finer resolution geographic range data
Other predictor variables	Forest loss used as a surrogate for habitat degradation Climate data not included	Included land cover and land use data within the model Include climate data
Model limitations		
Model selection	Only one type of model was tested	Re-run analysis using a variety of model types, for example classification trees, boosted trees and GLMs
Assumptions	Relationships in the training set are assumed to apply to non-assessed species	Further test the modelled relationships by repeating the analysis with species-specific data
Assessment bias	Training set includes both non-random (Red List) and random (Sampled Red List Index) assessments	Training set should comprise only randomly sampled/ SRLI species

Working Group system for the World Checklist of Selected Plant Families represents the most comprehensively compiled distribution data presently available for plants (WCSP, 2014), the high performance of these models has implications for future application to predict extinction risk for all plants when the checklist is complete. In line with previous studies, our findings indicate that human impacts and species range size are key drivers of extinction risk in bulbous monocots, providing much needed insight into correlates of threat in the group. Our model predicts that 35% of bulbous monocots may be threatened with extinction and highlights predicted hotspots of threat for systematic prioritization of species assessments. In an era of budget constraints for biodiversity assessments, our approach provides a low-cost option to achieving ambitious conservation targets based on limited information and financial investment.

ACKNOWLEDGEMENTS

We would like to thank E.J. Milner-Gulland (Imperial College London) and Walter Jetz (Yale University) for comments on the project proposal. We acknowledge the work of Masato Matoki and William Baker on modelling extinction risk in palms (Arecaceae) that inspired this study, and all contributors to open access data used in this research, without which the analysis would not have been possible, namely, the International Union for Conservation of Nature, Royal Botanic Gardens, Kew, Wildlife Conservation Society, Centre for International Earth Science Information Network, Columbia University, International Center for Tropical Agriculture, United Nations Environment Programme World Conservation Monitoring Centre and Hansen *et al.* (2013).

REFERENCES

Baillie, J.E.M., Collen, B., Amin, R., Akcakaya, R.H., Butchart, S.H.M., Brummitt, N., Meagher, T.R., Ram, M., Hilton-Taylor, C. & Mace, G.M. (2008) Towards monitoring global biodiversity. *Conservation Letters*, **1**, 18–26.

Bland, L.M., Collen, B., Orme, C.D.L. & Bielby, J. (2015a) Predicting the conservation status of data-deficient species. *Conservation Biology*, **29**, 250–259.

Bland, L.M., Orme, C.D.L., Bielby, J., Collen, B., Nicholson, E. & McCarthy, M.A. (2015b) Cost-effective assessment of extinction risk with limited information. *Journal of Applied Ecology*, **52**, 861–870.

Bland, L.M., Bielby, J., Kearney, S., Orme, C.D.L., Watson, J.E.M. & Collen, B. (2016) Toward reassessing data-deficient species. *Conservation Biology*, doi:10.1111/cobi.12850.

Boakes, E.H., McGowan, P.J.K., Fuller, R.A., Chang-qing, D., Clark, N.E., O'Connor, K. & Mace, G.M. (2010) Distorted views of biodiversity: spatial and temporal bias in species occurrence data. *PLoS Biology*, **8**, e1000385. doi:10.1371/journal.pbio.1000385.

Breiman, L., Friedman, J., Stone, C. & Olshen, R. (1984) *Classification and regression trees*. Chapman & Hall/CRC, London, UK.

Bruggeman, J., Herina, J. & Brandt, B.W. (2009) PhyloPars: estimation of missing parameter values using phylogeny. *Nucleic Acids Research*, **37**, W179–W184.

Brummitt, R.K., Pando, F. & Hollis, S. (2001) *Plant taxonomic database standards no. 2. World geographical scheme for recording plant distributions*. Hunt Institute for Botanical Documentation, Pittsburgh.

Brummitt, N., Bachman, S. & Moat, J. (2008) Applications of the IUCN Red List: towards a global barometer for plant diversity. *Endangered Species Research*, **6**, 127–135.

Brummitt, N.A., Bachman, S.P., Griffiths-Lee, J. *et al.* (2015) Green plants in the Red: a baseline global assessment for the IUCN Sampled Red List Index for plants. *PLoS ONE*, **10**, e0135152. doi:10.1371/journal.pone.0135152.

Bullock, J.M., Moy, I.L., Pywell, R.F., Coulson, S.J., Nolan, A.J. & Caswell, H. (2002) Plant dispersal and colonisation process at local and landscape scales. *Dispersal ecology* (ed.by J.M. Bullock, R.E. Kenward and R.S. Hails), pp. 279–302. Blackwell Publishing, Oxford, UK.

Burovalova, A., Bauert, M.R., Hassold, S., Fatroandrianjafinonjasolomiovazo, N.T. & Pin Koh, L. (2015) Relevance of global forest change data set to local conservation: case study of forest degradation in Masoala National Park, Madagascar. *Biotropica*, **47**, 267–274.

Callmander, M.W., Schatz, G.E. & Lowry, P.P. (2005) IUCN Red List assessment and the global strategy for plant conservation: taxonomists must act now. *Taxon*, **54**, 1047–1050.

Cardillo, M., Mace, G.M., Gittleman, J.L., Jones, K.E., Bielby, J. & Purvis, A. (2008) The predictability of extinction: biological and external correlates of decline in mammals. *Proceedings of the Royal Society, B: Biological sciences*, **275**, 1441–1448.

Chen, S., Kim, D., Chase, M.W. & Kim, J. (2013) Networks in a large-scale phylogenetic analysis: reconstructing evolutionary history of Asparagales (Lilianae) based on four plastid genes. *PLoS ONE*, **8**, e59472. doi:10.1371/journal.pone.0059472.

CIESIN & CIAT (2005) Gridded population of the world, version 3 (GPWv3): population density grid. NASA Socioeconomic Data and Applications Center (SEDAC). Available at: http://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-density. (accessed 24 April 2014).

CITES Trade Database (2016) *CITES trade statistics derived from the CITES Trade Database*, UNEP World Conservation Monitoring Centre, Cambridge, UK. Available at: https://trade.cites.org/.

Corlett, R.T. (2016) Plant diversity in a changing world: status, trends, and conservation needs. *Plant Diversity*, **38**, 10–16.

Cornwell, W.K., Westoby, M., Falster, D.S. *et al.* (2014) Functional distinctiveness of major plant lineages. *Journal of Ecology*, **102**, 345–356.

Davies, T.J., Smith, G.F., Bellstedt, D.U., Boatwright, J.S., Bytebier, B., Cowling, R.M., Forest, F., Harmon, L.J., Muasya, A.M., Schrire, B.D., Steenkamp, Y., van der Bank, M. & Savolainen, V. (2011) Extinction risk and diversification are linked in a plant biodiversity hotspot. *PLoS Biology*, **9**, e1000620. doi:10.1371/journal.pbio.1000620

Davis, A. (1999) *CITES bulb checklist*. Kew Publishing, Royal Botanic Gardens Kew, UK.

Di Marco, M. & Santini, L. (2015) Human pressures predict species' geographic range size better than biological traits. *Global Change Biology*, **21**, 2169–2178.

Di Marco, M., Buchanan, G.M., Szantoi, Z., Holmgren, M., Grottolo, Marsini G., Gross, D., Tranquilli, S., Boitani, L. & Rondinini, C. (2014) Drivers of extinction risk in African mammals: the interplay of distribution state, human pressure, conservation response and species biology. *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences*, **369**, 20130198. DOI: 10.1098/rstb.2013.0198

Diaz, S., Kattge, J., Cornelissen, H.C. *et al.* (2016) The global spectrum of plant form and function. *Nature*, **529**, 167–171.

Duffy, K.J., Kingston, N.E., Sayers, B.A., Roberts, D.L. & Stout, J.C. (2009) Inferring national and regional declines of rare orchid species with probabilistic models. *Conservation Biology*, **23**, 184–195.

Feeley, K.J. & Silman, M.R. (2009) Extinction risks of Amazonian plant species. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 12382–12387.

Fréville, H., McConway, K., Dodd, M. & Silvertown, J. (2007) Prediction of extinction in plants: interaction of extrinsic threats and life history traits. *Ecology*, **88**, 2662–2672.

García, N., Meerow, A.W., Soltis, D.E. & Soltis, P.S. (2014) Testing deep reticulate evolution in Amaryllidaceae tribe Hippeastreae (Asparagales) with ITS and chloroplast sequence data. *Systematic Botany*, **39**, 75–89.

Goettsch, B., Hilton-Taylor, C., Cruz-Piñón, G. *et al.* (2015) High proportion of cactus species threatened with extinction. *Nature Plants*, **1**, 15142. doi:10.1038/nplants.2015.142.

Hand, D.J. (2012) Assessing the performance of classification methods. *International Statistical Review*, **80**, 400–414.

Hansen, M., Potapov, P., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. (2013) High-resolution global maps of 21st-century forest cover change. *Science*, **342**, 850–853.

Hastie, T., Tibshirani, R. & Friedman, J. (2009) *The elements of statistical learning. Chapter 15: Random forests*. Springer, New York, USA.

IUCN (2001) *IUCN Red List categories and criteria: Version 3.1*, 2nd edn. IUCN, Gland, Switzerland and Cambridge, UK.

IUCN (2014) IUCN Red List of threatened species. Version 2014-2. Available at: www.iucnredlist.org. (accessed 28 July 2014).

IUCN (2015) IUCN Red List of threatened species. Version 2015-4. Available at: www.iucnredlist.org. (accessed 12 November 2015).

IUCN (2016) IUCN Red List of threatened species. Version 2016-2. Available at: www.iucnredlist.org. (accessed 25 October 2016).

IUCN Standards and Petitions Subcommittee (2014) Guidelines for using the IUCN Red List Categories and Criteria. Version 11 (February 2014). Prepared by the Standards and Petitions Working Group of the IUCN SSC Biodiversity Assessments SubCommittee in August 2008, 1, 86.

IUCN and UNEP-WCMC (2014) The world database on protected areas (WDPA). Available at: www.protectedplanet.net. UNEP-WCMC, Cambridge, UK. (accessed 24 April 2014).

Jetz, W. & Freckleton, R.P. (2015) Towards a general framework for predicting threat status of data-deficient species from phylogenetic, spatial and environmental information. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, **370**, 20140016. DOI: 10.1098/rstb.2014.0016.

Juffe-Bignoli, D., Brooks, T.M., Butchart, S.H.M. *et al.* (2016) Assessing the cost of global biodiversity and conservation knowledge. *PLoS ONES*, **11**, e0160640. doi:10.1371/journal.pone.0160640.

Kuhn, M. (2008) Building predictive models in R using the caret package. *Journal of Statistical Software*, **28**, 1–26.

Laliberté, E. (2016) Below-ground frontiers in trait-based plant ecology. *New Phytologist*, doi:10.1111/nph.14247.

Lee, T.M. & Jetz, W. (2010) *Unravelling the structure of species extinction risk for predictive conservation science*. Proceedings of the Royal Society B, Biological Sciences. doi:10.1098/rspb.2010.1877.

Luiz, O.J., Woods, R.M., Madin, E.M.P. & Madin, J.S. (2016) Predicting IUCN extinction risk categories for the world's data deficient groupers (Teleostei: Epinephelidae). *Conservation Letters*, **9**, 342–350.

Machado, N. & Loyola, R.D. (2013) A comprehensive quantitative assessment of bird extinction risk in Brazil. *PLoS ONE*, **8**, e72283. doi:10.1371/journal.pone.0072283.

Marshall, N.T. (1993) *The gardener's guide to plant conservation*. World Wildlife Fund-US, Washington DC, USA.

Murray, K.A., Verde Arregoitia, L.D., Davidson, A., Di Marco, M. & Di Fonzo, M.M.I. (2014) Threat to the point: improving the value of comparative extinction risk analysis for conservation action. *Global Change Biology*, **20**, 483–494.

Newton, R., Davis, A., Rutherford, C., Trias-Blasi, A., Trivedi, C. & Wilford, R. (2014) *Conservation and sustainable use of snowdrops*. RHS Daffodil, Snowdrop and Tulip Yearbook.

Özhatay, N., Koçyiğit, M., Yüzbaşıoğlu, S. & Gürdal, B. (2013) Mediterranean flora and its conservation in Turkey: with special reference to Monocot geophytes. *Flora Mediterranea*, **23**, 195–208.

Pearce, J. & Ferrier, S. (2000) Evaluating the predictive performance of habitat models developed using logistic regression. *Ecological Modelling*, **133**, 225–245.

Perkins, N. & Schisterman, E. (2006) The inconsistency of "optimal" cutpoints obtained using two criteria based on the receiver operating characteristic curve. *American Journal of Epidemiology*, **163**, 670–675.

Possingham, H.P., Andelman, S.J., Burgman, M.A., Medellín, R.A., Master, L.L. & Keith, D.A. (2002) Limits to the use of threatened species lists. *Trends in Ecology & Evolution*, **17**, 503–507.

Purvis, A., Gittleman, J.L., Cowlishaw, G. & Mace, G.M. (2000) Predicting extinction risk in declining species. *Proceedings of the Royal Society B: Biological Sciences*, **267**, 1947–1952.

Purvis, A., Cardillo, M., Grenyer, R. & Collen, B. (2005) Correlates of extinction risk: phylogeny, biology, threat and scale. *Phylogeny and conservation* (ed.by A. Purvis, T.M. Brooks and J.L. Gittleman), pp. 295–316. Cambridge University Press, Cambridge, UK.

Pywell, R.F., Bullock, J.M., Roy, D.B., Warman, L.I.Z., Walker, K.J. & Rothery, P. (2003) *Journal of Applied Ecology*, **40**, 65–77.

R Core Development Team (2014) Version 3.0.2. Available at: http://www.r-project.org/. (accessed 30 April 2014).

Rodrigues, A.S., Pilgrim, J.D., Lamoreux, J.F., Hoffmann, M. & Brooks, T.M. (2006) The value of the IUCN Red List for conservation. *Trends in Ecology & Evolution*, **21**, 71–76.

Rondinini, C., Di Marco, M., Visconti, P., Butchart, S.H.M. & Boitani, L. (2014) Update or outdate: long-term viability of the IUCN Red List. *Conservation Letters*, **7**, 126–130.

Royal Botanic Gardens, Kew (2010) *Plants under pressure—a global assessment: the first report of the IUCN sampled red list index for plants*. Royal Botanic Gardens, Kew, UK.

SANBI (2014) Red List of South African Plants. Version 2014.1. Available at: redlist.sanbi.org. (accessed 14 July 2014).

Seberg, O., Petersen, G., Davies, J.I., Pires, J.C., Stevenson, D.W., Chase, M.W., Fay, M.F., Devey, D.S., Jørgensen, T., Sytsma, K.J. & Pillon, Y. (2012) Phylogeny of the Asparagales based on three plastid and two mitochondrial genes. *American Journal of Botany*, **99**, 875–889.

Sharrock, S., Oldfield, S. & Wilson, O. (2014) *Plant Conservation Report 2014: a review of progress in implementation of the global strategy for plant conservation 2011–2020*. Secretariat of the Convention on Biological Diversity, Montréal, Canada and Botanic Gardens Conservation International, Richmond, UK. Technical Series No. 81, 56 pages. Available at: https://www.cbd.int/doc/publications/cbd-ts-81-en.pdf. (accessed 7 April 2016).

Smith, R.J., Veríssimo, D., Leader-Williams, N., Cowling, R.M. & Knight, A.T. (2009) Let the locals lead. *Nature*, **462**, 280–281.

Smith, M.J., Benítez-Díaz, H., Africa, Clemente-Muñoz M., Donaldson, J., Hutton, J.M., Noel, McGough H., Medellin, R.A., Morgan, D.H.W., O'Criodain, C., Oldfield, T.E.E., Schippman, W. & Williams, R.J. (2011) Assessing the impacts of international trade on CITES-listed species: current practises and opportunities for scientific research. *Biological Conservation*, **144**, 82–91.

The Plant List (2013) Version 1.1. Available at: http://www.theplantlist.org/. (accessed 18 December 2015).

UN Comtrade (2014) United Nations Commodity Trade Statistics Database. Available at: http://comtrade.un.org/db/default.aspx

UNEP-WCMC (2015) *World database on protected areas user manual 1.0*. Cambridge, UK, UNEP-WCMC.

WCS (2005) Last of the Wild Project, Version 2, 2005, (LWP-2): Global Human Footprint Dataset (Geographic). Palisades, New York: NASA Socioeconomic Data and Applications Center (SEDAC). Available at: https://doi.org/10.7927/H4M61H5F. (accessed 26 April 2014).

WCSP (2014) *World checklist of selected plant families*. Royal Botanic Gardens, Kew, UK.

Yüzbaşioğlu, S. (2008) The development of non-detriment findings for Galanthus elwesii Hook. F., in Turkey. International Expert Workshop on CITES Non-Detriment Findings, Cancun. Available at: http://www.conabio.gob.mx/institucion/cooperacion_internacional/TallerNDF/Links-Documentos/WG-CS/WG4-GeophytesandEpiphytes/WG4-CS7%20Galanthusel2/WG4-CS7.pdf.

DATA ACCESSIBILITY

R script for this analysis is available on GitHub: https://github.com/sdarrah/extinctionrisk-plants.git.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Supplementary tables and figures.

Appendix S2 Online database of model results.

Figure S1.1 Random forest predictions for validation set.

Figure S1.2 Variable importance for model based on fine-scale range species distribution data.

Figure S1.3 Partial dependence plots showing likelihood of extinction risk for predictor variables.

Table S1.1 Number of bulbous monocotyledon species used in the analysis by plant family.

Table S1.2 Proportion of assessed bulbous monocotyledon species correctly classified by the model.

Table S1.3 Performance statistics for models based on IUCN Red List and SRLI assessed bulbous monocotyledon species.

Table S1.4 Performance statistics for model based on species with fine-scale species distribution data.

Table S2 Online database of model results showing predicted extinction risk for assessed and non-assessed bulbous monocotyledon species.

BIOSKETCH

Sarah Darrah is interested in plant biodiversity indicators and the application of extinction risk modelling to conservation prioritization schemes.

Author contributions: All authors contributed to research design and writing of the manuscript. A.T.-B. and S.B. jointly conceived the main objectives. Data were supplied from multiple sources as outlined in the text and references. L.B. provided coding script and S.D. carried out the modelling and analysis.

Editor: Kenneth Feeley

Comprehensive Red List Assessment Reveals Exceptionally High Extinction Risk to Madagascar Palms

Mijoro Rakotoarinivo[1]*, John Dransfield[2], Steven P. Bachman[2], Justin Moat[2], William J. Baker[2]

1 Kew Madagascar Conservation Centre, Ambodivoanjo Ivandry, Antananarivo, Madagascar, 2 Royal Botanic Gardens, Kew, Richmond, Surrey, United Kingdom

Abstract

The establishment of baseline IUCN Red List assessments for plants is a crucial step in conservation planning. Nowhere is this more important than in biodiversity hotspots that are subject to significant anthropogenic pressures, such as Madagascar. Here, all Madagascar palm species are assessed using the IUCN Red List categories and criteria, version 3.1. Our results indicate that 83% of the 192 endemic species are threatened, nearly four times the proportion estimated for plants globally and exceeding estimates for all other comprehensively evaluated plant groups in Madagascar. Compared with a previous assessment in 1995, the number of Endangered and Critically Endangered species has substantially increased, due to the discovery of 28 new species since 1995, most of which are highly threatened. The conservation status of most species included in both the 1995 and the current assessments has not changed. Where change occurred, more species have moved to lower threat categories than to higher categories, because of improved knowledge of species and their distributions, rather than a decrease in extinction risk. However, some cases of genuine deterioration in conservation status were also identified. Palms in Madagascar are primarily threatened by habitat loss due to agriculture and biological resource use through direct exploitation or collateral damage. The recent extension of Madagascar's protected area network is highly beneficial for palms, substantially increasing the number of threatened species populations included within reserves. Notably, three of the eight most important protected areas for palms are newly designated. However, 28 threatened and data deficient species are not protected by the expanded network, including some Critically Endangered species. Moreover, many species occurring in protected areas are still threatened, indicating that threatening processes persist even in reserves. Definitive implementation of the new protected areas combined with local community engagement are essential for the survival of Madagascar's palms.

Citation: Rakotoarinivo M, Dransfield J, Bachman SP, Moat J, Baker WJ (2014) Comprehensive Red List Assessment Reveals Exceptionally High Extinction Risk to Madagascar Palms. PLoS ONE 9(7): e103684. doi:10.1371/journal.pone.0103684

Editor: Francisco Moreira, Institute of Agronomy, University of Lisbon, Portugal

Received January 9, 2014; **Accepted** May 9, 2014; **Published** July 30, 2014

Funding: This work was funded by the Friends of Kew through the Threatened Plants Appeal and by the Bentham-Moxon Trust at the Royal Botanic Gardens, Kew. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* Email: mrakotoarinivo.rbgkew@moov.mg

Introduction

Madagascar is one of the World's most threatened biodiversity hotspots [1] because of the high endemism of its biota coupled with widespread habitat degradation, especially in humid forest areas. Despite ongoing scientific studies that have highlighted Madagascar as a place of endemic megadiversity that is facing intensifying extinction risk [2], the island's charismatic flora and fauna remain under immense pressure [3,4]. Conservation baselines are urgently required to demonstrate and strengthen the case for action on the ground.

Palms are among the most conspicuous components of the flora of Madagascar. To date, 195 species in 17 genera are recognized [5,6] with all but three being endemic to the island (98% endemism). The palm flora of Madagascar is outstandingly rich in a global context [7]. Palms inhabit mostly primary vegetation although a few species occur in disturbed areas, such as anthropogenic grassland. Consistent with global patterns of palm distribution, 90% of Madagascar palms are restricted to humid forest [8,9].

Palms are particularly vulnerable to humid forest degradation. In most species, survival and recruitment are reduced when habitat quality declines [10,11] or when habitats become fragmented [12]. The extensive degradation of Madagascar's humid forests, which have been reduced to around 25% of their original extent [13], implies that the island's humid forest-restricted biota, such as palms, are likely to be extremely threatened.

In addition to habitat loss, palms are further threatened by unsustainable, targeted exploitation by humans. Alongside grasses and legumes, palms are among the most important plant families for humans [14], providing numerous useful resources, such as materials for construction or weaving, food, medicine and ornamental plants [15]. Palms play a particularly important role in poorer countries, such as Madagascar, where they have immense economic importance at the village level [10], but they are often destructively harvested, e.g. for palm heart consumption or construction materials. In recent decades, Madagascar palms have also been targeted by plant collectors for introduction to horticultural trade [16]. These human activities place palms at greater risk of extinction than other humid forest groups that are not exploited in this way.

Extinctions at both species and population levels are of concern because unique evolutionary history and ecosystem services may be lost [17], which is particularly significant in the case of keystone groups such as palms [9]. To prevent such biodiversity loss in

Madagascar palms, a critical conservation strategy is required to focus attention on conservation priorities, to stimulate necessary actions and to raise public awareness. To take these steps, species of concern must first be properly identified based on sound taxonomy [18] so that accurate and cost-effective conservation management decisions can be made. The conservation performance of protected area networks can be improved with such information. Much of Madagascar's biodiversity is unlikely to survive unless it occurs within protected areas [19,20]. In 2003, the Madagascar government decided to increase the protected areas surface [21] from 1.7 million hectares (3%) [22] to 6 million hectare (10% of the island's surface [23]) as many unprotected areas were found to be critically important for biodiversity [24,25].

The International Union for the Conservation of Nature (IUCN) curates the IUCN Red List of Threatened Species, which is the most comprehensive, objective and authoritative data source on extinction risk in species [26–28]. Through the application of a set of five criteria (e.g. restricted range, declining population), a species can be classified according to its relative risk of extinction. In an earlier assessment of the palms of Madagascar [10], in which previous versions of the IUCN system [29,30] were applied, 113 species were identified as threatened and 18 presumed extinct. In this paper, we present a complete and updated conservation assessment of all palm species in Madagascar using the current IUCN Red List categories and criteria (version 3.1 [31]). This work builds upon a robust taxonomy for the group established in recent years [10,32,33,34] and a comprehensive database of collections and observations from recent field work [6].

The objective of this study is to produce a baseline conservation dataset for palms in Madagascar including taxonomy, species distributions, ecological factors and economic uses. We analyze this dataset to answer the following questions: 1) what is the current extinction risk to Madagascar's endemic palm species, 2) how does current status compare with the previous assessment in 1995, 3) is the existing protected area network effective for palms and 4) what are the major threats to palms?

Methods

Study area

Madagascar is a large tropical island (592,750 km^2) in the Indian Ocean [35] and is the third largest tropical island in the world, after New Guinea and Borneo. The island has a complex landscape [36] and is dominated by mountains running north-south, resulting in a central highland region above 800 m elevation. On the eastern side of the central highland is an escarpment that falls steeply away towards the Indian Ocean, whereas the western side consists of a large plain declining gently to the Mozambique Channel. Due to the impact of the southeastern tradewinds (Alizé) and the northwestern monsoon from the Equator, the eastern region is humid to perhumid, the highlands are relatively temperate, the western region is subhumid to dry, and the far south-west is subarid [37]. Consequently, the island has a great diversity of primary vegetation types, ranging from humid forest to dry spiny forest (Fig. 1a) [13]. Humid forest, the primary habitat of most palms, is restricted to the east and north-west of the island. Of the estimated 21 million inhabitants, nearly 80% live in rural areas [38] and depend on natural resources for their subsistence, contributing to the destruction of Madagascar's forests, which have declined by 40% between 1950 and 2000 alone [39].

Occurrence data

The study is based on a dataset of 2,160 georeferenced occurrence records, derived from herbarium specimens of Madagascar palms in key botanical institutions around the world: AAU, FTG, GE, K, MO, NY, P, TAN, TEF and ZT (herbarium acronyms follow [40]). Collection dates range from 1834 to 2010. Records lacking geographic coordinates on specimen labels were georeferenced using topographic maps, online gazetteers, the Madagascar gazetteer of the Missouri Botanical Garden [41] and online mapping tools such as Google Earth [42].

Of the georeferenced records, 820 (38%) postdate 1995 when the previous conservation assessment was conducted [10] of which 561 (26%) result from our own fieldwork in Madagascar since 1995 (fig. 1a). Building on the robust taxonomic baseline provided by Dransfield and Beentje [10], we have conducted targeted fieldwork in 32 sites (Table 1) across Madagascar between 1995–2010 (Fig. 1a), focusing mostly on primary forest areas far from high human density where the palm flora is rich, but poorly known (Fig. 1b). This fieldwork has substantially improved our understanding of the distribution and the populations of 152 species (78% of the total palm flora). The number of specimen records per species ranges from 1 to 85 (mean: 10 specimens per species) and 107 species are known from fewer than 5 specimen records.

All fieldwork was conducted with prior informed consent of the necessary authorities (Table 1). Permission for all fieldwork activities was obtained from the Ministry of Environment and Forests (Ministère de l'Environnement et des Forêts). Additional permissions were required depending on the status of the area visited. For National Parks and Special Reserves, additional permits were issued by Madagascar National Parks (MNP). For Système des Aires Protégées de Madagascar (SAPM) Reserves, additional fieldwork permission was sought from the specific management authority of each site (Table 1). For Local Community Forests, the local village council (Communauté de Base, COBA) was consulted on arrival. Fieldwork on private lands required permission from the land owners in advance (Table 1). Herbarium specimens from our fieldwork were deposited at the Madagascar national herbarium at Parc Botanique et Zoologique de Tsimbazaza (TAN) and the Royal Botanic Gardens, Kew (K). Additional duplicates, where available, were distributed primarily to the Missouri Botanical Garden (MO) and the Natural History Museum, Paris (P).

IUCN Red List Conservation Assessments

We conducted a complete assessment of the conservation status of all 192 endemic Madagascar palm species using the IUCN Red List categories and criteria, version 3.1 [31] with reference to the latest guidelines [43]. Assessments were independently reviewed and verified by the IUCN Palm Specialist Group Red List Authority and IUCN Red List Unit. They were subsequently published on-line on the IUCN Red List on 17 October 2012 [44]. All assessments are now accessible via the IUCN Red List web portal at www.iucnredlist.org.

Each species was classified according to one of the following IUCN categories: Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC) or Data Deficient (DD). We used data from our palm occurrence dataset to summarise distribution, population size and threats to species in order to apply the quantitative Red List criteria. Although attempts were made to apply all five criteria in the Red List system (A, declining population; B, geographic range size and fragmentation, decline, or fluctuations; C, small population size and fragmentation, decline or fluctuations; D, very small population; E, quantitative analysis of extinction risk), as

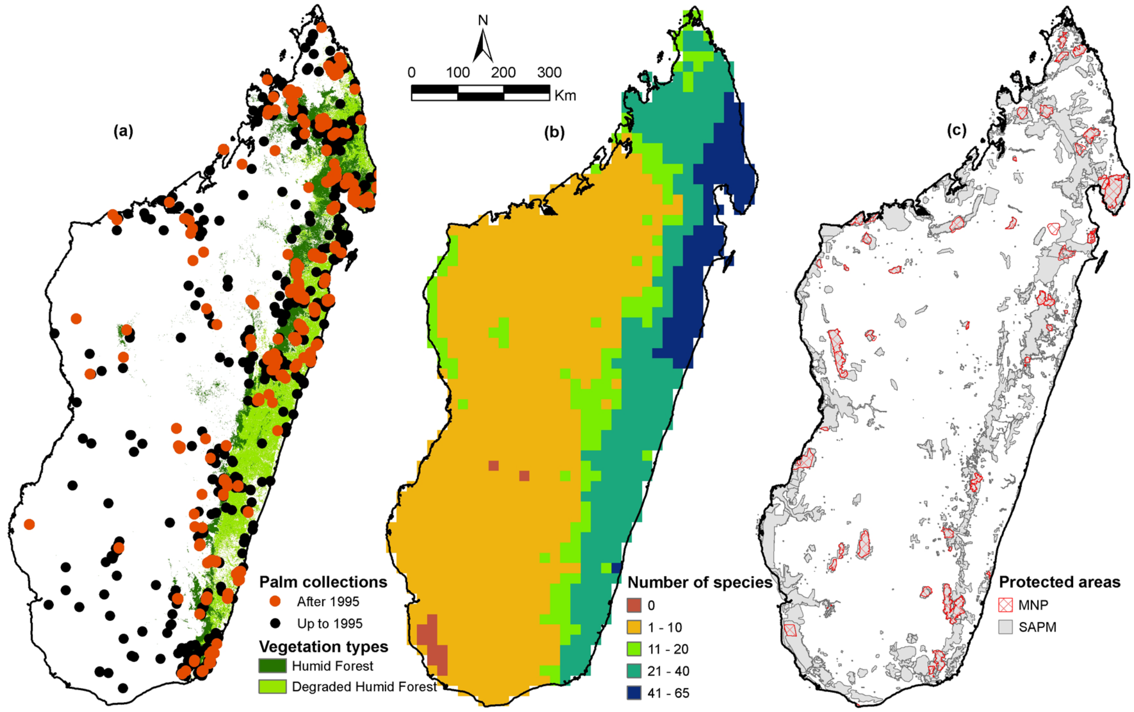


Figure 1. Palm distributions, humid forest and protected areas in Madagascar. (a) Palm specimen collection localities in Madagascar and extent of humid forest vegetation [13]. (b) Species richness of palms in Madagascar [6] illustrating predicted number of palm species across the island at a resolution of 0.2° (ca. 22 km × 22 km). (c) Protected area network in Madagascar comprising the long-standing MNP network (46 parks and reserves [50]) and the newly established SAPM (145 reserves, including those of the MNP network [23]).
doi:10.1371/journal.pone.0103684.g001

recommended by IUCN, most assessments were conducted using criterion B due to the limitations of available data, a common pattern for Red List assessments of plants and some other groups [45].

The palm occurrences were carefully scrutinised for georeference precision, taxonomic identification and likelihood of a population still being extant e.g. historical collections in areas now deforested were excluded. The geographic range of each species was then quantified using two metrics, extent of occurrence (EOO) and area of occupancy (AOO) [31], both of which can be used for assessments under criterion B (restricted range species). EOO was calculated by constructing the minimum convex polygon (convex hull) around known occurrences [46,47] using the Conservation Assessment Tools extension to ArcView [48]. AOO was calculated with the same tools by overlaying a grid and interpreting known occurrences as occupied grid cells. The sum of occupied grid cells equates to the AOO value. A grid cell size of 2×2 km^2 was applied, as recommended by IUCN [43], where sampling effort was deemed sufficient. In some cases, larger cell sizes were used (up to 10×10 km^2 [25,46]) to account for inadequate sampling across the range. These larger grid cells were not scaled down to the reference scale of 2×2 km^2, so the assessments assume the distribution is fully saturated at the 2×2 km^2 reference scale [43]. In cases where a species was known from less than three unique collection sites, EOO could not be calculated and AOO alone was estimated. For species known to occur at a single locality and in a well defined habitat, AOO was estimated by considering the available suitable habitat. Satellite imagery from Google Earth [42] was used to determine suitable areas and polygons were drawn to estimate area of occupancy (AOO).

To infer population trends, such as continuing decline or fragmentation of distribution range through time, GIS layers of the vegetation maps of Humbert & Cours-Darne [49] and Moat & Smith [13] were compared. The rate of the decline of the population of each species in the 42 years between these two baseline vegetation surveys (1965 and 2007) was then calculated from the loss of suitable habitat under its EOO and AOO.

In order to evaluate the trend in conservation status change over time, we compared the 2012 assessment [44] with the previous assessment made by Dransfield & Beentje [10]. The two assessments were based on different versions of the IUCN Red List categories and criteria. The 1995 assessment was broadly based on version 2.3 [29], whereas the 2012 assessment used version 3.1 [31]. While most Red List categories were comparable between the two assessments, the category "Rare" used by Dransfield and Beentje [10] comes from a scheme pre-dating version 2.3 and could not be related to a category in version 3.1. The category "Near Threatened" of version 3.1 was absent from version 2.3. "Not Threatened" (NotT), as used in the 1995 assessment, was regarded as equivalent to "Least Concern" in version 3.1. The change in the IUCN assessments was quantified for data sufficient species (i.e. those that had enough data to carry out a full assessment) that were assessed in both years and in comparable categories. Changes were sorted into three classes: a) no change, if the category of the species was the same in the two assessments, b) downlisted, if the assessment of extinction risk decreased, i.e. from higher to lower category (e.g. EN to VU) and

Table 1. Fieldwork locations visited by the authors.

Location	Latitude and longitude co-ordinates of sites visited	Status
Ambakireny	17.69° S 48.01° E	Local community forest
Ambatovaky	16.86° S 49.26° E	Special Reserve
Ambodivoahangy (Makira)	15.28° S 49.62° E	Local community forest
Analalava (Mahajanga)	14.76 S° 47.43° E	Local community forest
Andilamena	16.98° S 48.84° E; 16.81° S 48.68° E	Local community forest
Anosibe an'Ala	19.66° S 48.11° E	Local community forest
Betafo	20.20° S 46.50° E	Local community forest
Betampona	17.91° S 49.20° E	Special Reserve
Brickaville	18.89° S 49.12° E; 18.96° S 48.85° E	Local community forest
Daraina	13.26° S 49.59° E	SAPM Reserve (managed by Fanamby)
Fenoarivo Atsinanana	17.29° S 49.41° E	SAPM Reserve (managed by Ecole Supérieure des Sciences Agronomiques- Forêts, Antananarivo)
Fort-Dauphin	24.77° S 47.18° E	Private Land (managed by Qit Minerals Madagascar/Rio Tinto)
	24.56° S 47.20° E	SAPM Reserve (managed by Asity Madagascar/Bird Life International)
Analalava (Foulpointe)	17.71° S 49.45° E	SAPM Reserve (managed by Missouri Botanical Gardens)
Ifanadiana	21.33° S 47.71° E	Local community forest
Itremo	20.57° S 46.56° E	SAPM Reserve (managed by Kew Madagascar Conservation Centre)
Maevatanana	16.76° S 47.03° E	Local community forest
Makira	15.38° S 49.44° E; 15.28° S 49.44° E	SAPM Reserve (managed by Wildlife Conservation Society)
Manakara	21.83° S 47.90° E	Local community forest
Mananara Avaratra	15.94° S 49.54° E	Local community forest
Mangerivola	18.20° S 48.92° E	Special Reserve
Mantadia	18.88° S 48.44° E	National Park
Masoala	15.31° S 49.85° E; 15.73° S 49.96° E, 15.74° S 50.19° E, 15.77° S 50.07° E	National Park
Midongy Atsimo	23.55° S 47.08° E	National park
Soanierana Ivongo	16.68° S 49.60° E	Local community forest
Vondrozo	22.80° S 47.18° E	Local community forest

doi:10.1371/journal.pone.0103684.t001

c) uplisted, if the assessment of extinction risk increased, i.e. from lower to higher category (e.g. VU to EN).

Protected area coverage

We compared the distribution of all species to the protected area network in order to assess the effectiveness and coverage of reserves for palm conservation. We used GIS layers (Fig. 1c) describing the 46 established protected areas within the MNP network [50] and the new protected area network being established by SAPM since 2011, which comprises 145 reserves, including those of MNP [23]. We assessed the relative threat status of species occurring in zero, one and two or more protected area to test the expectation that species occurring in fewer protected areas have higher threat ratings.

Threats

During the assessment process the dominant threats for each species were classified according to the IUCN Threats Classification Scheme (version 3.2) [51]. Details about the threats and the local utilization of each species were obtained from expert field observations, specimen labels and literature sources. These data were later compiled to evaluate the relative importance of major threatening processes affecting palms in Madagascar.

Results

IUCN Red List Conservation Assessments

The results of our complete assessment of the conservation status of all known Madagascar palms are summarised in Table 2 and Figure 2, with a detailed break-down given in Table 3. Of the data sufficient species (179), we found that 149 (78%) are classified as threatened (CR, EN or VU). Thirteen species were not data sufficient and were thus rated as DD. Data on the current status of these species were inadequate to complete an assessment primarily because most were known only from the type collection and have not been observed for many years. Taking into account the 13 DD species, we estimated 'lower', 'best estimate' ('mid-point') and 'upper' bounds of the percentage of threatened species [52], which were 78%, 83% and 84% respectively. The lower bound treats all DD species as unthreatened, whereas the upper bound assumes that all are threatened. The best estimate assumes that the same fraction of DD species are threatened as was found for data sufficient species. A total of 14 species were listed as NT, which

Table 2. Summary of results from the 2012 IUCN Red List Assessment of Madagascar Palms.

	Count	Percentage
IUCN Red List category		
Extinct (EX)	0	0
Extinct in the Wild (EW)	0	0
Critically Endangered (CR)	61	32
Endangered (EN)	45	23
Vulnerable (VU)	43	22
Near Threatened (NT)	14	7
Least Concern (LC)	16	8
Data Deficient (DD)	13	7
Summary Statistics		
Total Evaluated	192	100
Total Data Sufficient (CR+EN+VU+NT+LC)	179	93
Total Threatened – lower bound (CR+EN+VU)	149	78
Total Threatened – best estimate (mid-point) (CR+EN+VU+((Total Threatened/Data Sufficient) × DD))	160	83
Total Threatened – upper bound (CR+EN+VU+DD)	162	84
Total Species of Elevated Conservation Concern (CR+EN+VU+NT)	163	85
Total Not Threatened (LC+DD)	30	16

doi:10.1371/journal.pone.0103684.t002

gives a total of 163 (91%) species considered to be of elevated conservation concern. Only 16 species were listed as LC.

Comparison with 1995 assessments

Comparison between the 1995 assessments and the 2012 assessments is complicated due to the change in Red List criteria from earlier versions to version 3.1 [29–31], improved knowledge of species distributions and changes to the overall taxonomy of Madagascar palms due to many new species being described after 1995. Consequently, a Red List Index approach [53,54] was not used here. Figure 3a illustrates numbers of species assessed in each of the IUCN Red List categories for categories that are

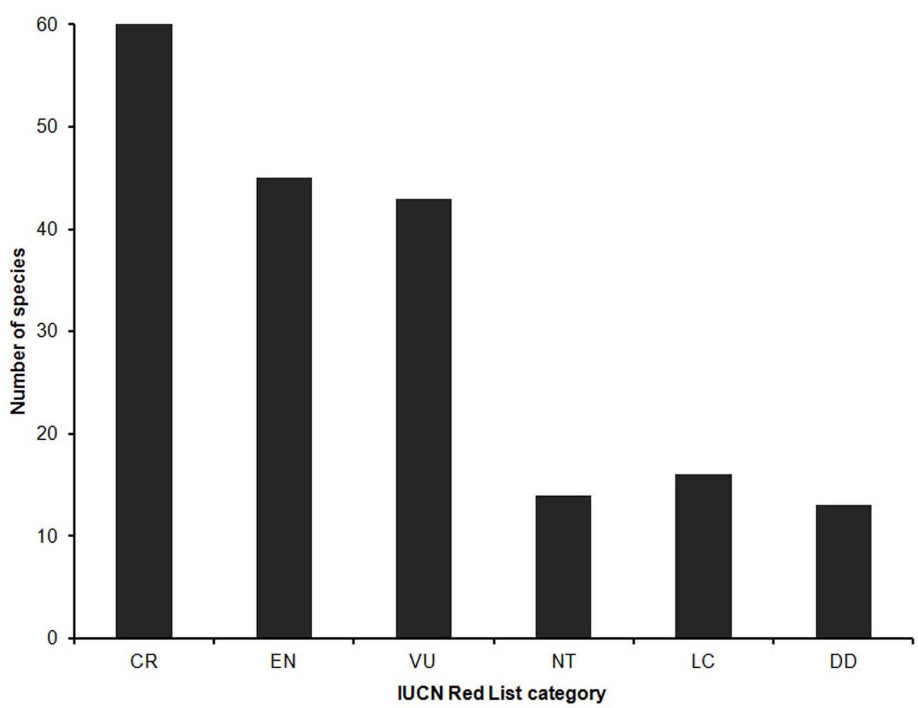


Figure 2. Summary of the 2012 IUCN Red List Assessments of Madagascar Palms (see table 2). IUCN Red List categories: Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), Data Deficient (DD) [31].
doi:10.1371/journal.pone.0103684.g002

Table 3. The conservation status of all 192 endemic Madagascar palm species.

Species	2012 Red List Assessment	1995 Red List Assessment	EOO (km^2)	AOO (km^2)	Status change	Populations in protected areas: MNP only (%)	Populations in protected areas: SAPM (%)
Beccariophoenix alfredii	VU	–	8	5	Described post-1995	0	0
Beccariophoenix madagascariensis	VU	CR	15460	300	Downlisted	30	80
Bismarckia nobilis	LC	NotT	319415	17100	No change	20	60
Borassus madagascariensis	EN	VU	48872	350	Uplisted	0	40
Dypsis acaulis	EN	EW	72	8	Downlisted	30	30
Dypsis acuminum	EN	DD	12113	150	Not comparable	50	80
Dypsis albofarinosa	CR	–	4	4	Described post-1995	100	100
Dypsis ambanjae	CR	EW	1767	150	Downlisted	50	100
Dypsis ambilaensis	EN	EN	176	60	No change	0	60
Dypsis ambositrae	CR	CR	1790	150	No change	0	30
Dypsis andapae	EN	Rare	1428	35	Not comparable	70	70
Dypsis andilamenensis	CR	–	10	5	Described post-1995	0	0
Dypsis andrianatonga	VU	Rare	5909	288	Not comparable	90	90
Dypsis angusta	EN	EN	5760	123	No change	40	70
Dypsis angustifolia	EN	Rare	469	327	Not comparable	30	100
Dypsis anjae	CR	–	4	4	Described post-1995	100	100
Dypsis ankaizinensis	DD	DD	–	–	No change	–	–
Dypsis ankirindro	NT	–	14	4	Described post-1995	0	100
Dypsis antanambensis	CR	EN	6	6	Uplisted	100	100
Dypsis aquatilis	CR	EN	35	25	Uplisted	0	0
Dypsis arenarum	CR	CR	895	36	No change	0	70
Dypsis baronii	LC	NotT	239065	6075	No change	40	70
Dypsis basilonga	CR	EN	188	16	Uplisted	0	0
Dypsis beentjei	CR	EN	6	6	Uplisted	100	100
Dypsis bejofo	VU	EN	10322	150	Downlisted	60	80
Dypsis bernierana	VU	VU	14610	600	No change	50	60
Dypsis betamponensis	VU	EW	4	4	Downlisted	100	100
Dypsis betsimisarakae	VU	–	7995	512	Described post-1995	50	80
Dypsis boiviniana	EN	EN	7196	896	No change	30	60
Dypsis bonsai	VU	VU	14420	520	No change	80	90
Dypsis bosseri	EN	EW	4	1.5	Downlisted	0	90
Dypsis brevicaulis	CR	CR	380	135	No change	0	80
Dypsis brittiana	CR	–	4	4	Described post-1995	0	100
Dypsis canaliculata	CR	EW	4114	243	Downlisted	30	70
Dypsis canescens	DD	EW	–	–	Not comparable	–	–

Table 3. Cont.

Species	2012 Red List Assessment	1995 Red List Assessment	EOO (km^2)	AOO (km^2)	Status change	Populations in protected areas: MNP only (%)	Populations in protected areas: SAPM (%)
Dypsis carlsmithii	CR	–	2041	8	Described post-1995	50	100
Dypsis catatiana	LC	NotT	146761	3300	No change	70	80
Dypsis caudata	CR	CR	4	4	No change	100	100
Dypsis ceracea	EN	EW	11211	225	Downlisted	40	100
Dypsis commersoniana	DD	CR	–	–	Not comparable	–	–
Dypsis concinna	NT	VU	30591	2100	Downlisted	30	100
Dypsis confusa	NT	Rare	49262	1216	Not comparable	60	70
Dypsis cookei	CR	EN	6	4	Uplisted	100	100
Dypsis coriacea	NT	VU	11642	910	Downlisted	80	90
Dypsis corniculata	EN	VU	18147	1350	Uplisted	40	40
Dypsis coursii	LC	VU	3737	256	Downlisted	70	100
Dypsis crinita	NT	Rare	67442	1134	Not comparable	60	90
Dypsis culminis	EN	–	564	10	Described post-1995	0	100
Dypsis curtisii	EN	DD	7185	64	Not comparable	60	90
Dypsis decaryi	VU	VU	339	83	No change	40	40
Dypsis decipiens	VU	EN	42846	1430	Downlisted	20	40
Dypsis delicatula	VU	–	8	8	Described post-1995	40	80
Dypsis digitata	CR	CR	2334	8	No change	40	40
Dypsis dracaenoides	EN		4	4	Described post-1995	0	0
Dypsis dransfieldii	NT	EN	12	8	Downlisted	100	100
Dypsis elegans	CR	CR	1340	27	No change	40	70
Dypsis eriostachys	EN	EN	2395	20	No change	40	70
Dypsis faneva	EN	EN	2037	94	No change	50	90
Dypsis fanjana	EN	EN	10772	110	No change	80	80
Dypsis fasciculata	NT	VU	74598	2304	Downlisted	40	70
Dypsis fibrosa	LC	NotT	160135	4400	No change	40	60
Dypsis forficifolia	LC	NotT	29506	4500	No change	40	80
Dypsis furcata	EN	EW	7914	25	Downlisted	0	50
Dypsis gautieri	VU	–	6	3	Described post-1995	0	100
Dypsis glabrescens	EN	EN	3195	61	No change	60	70
Dypsis gronophyllum	CR	–	4	4	Described post-1995	0	0
Dypsis henrici	DD	DD	–	–	No change	–	–
Dypsis heteromorpha	DD	DD	–	–	No change	–	–
Dypsis heterophylla	NT	Rare	91693	1225	Not comparable	40	60
Dypsis hiarakae	VU	VU	17316	700	No change	70	90

Table 3. Cont.

Species	2012 Red List Assessment	1995 Red List Assessment	EOO (km^2)	AOO (km^2)	Status change	Populations in protected areas: MNP only (%)	Populations in protected areas: SAPM (%)
Dypsis hildebrandtii	NT	VU	22794	1700	Downlisted	40	60
Dypsis hovomantsina	CR	CR	5225	288	No change	60	100
Dypsis humbertii	VU	VU	10780	810	No change	40	80
Dypsis humilis	CR	–	4	4	Described post-1995	0	0
Dypsis ifanadianae	CR	CR	25	6	No change	0	0
Dypsis integra	EN	CR	35824	294	Downlisted	40	70
Dypsis intermedia	CR	CR	4	4	No change	100	100
Dypsis interrupta	CR	CR	378	10	No change	40	60
Dypsis jeremiei	CR	–	4	4	Described post-1995	100	100
Dypsis jumelleana	VU	VU	15117	1100	No change	40	40
Dypsis laevis	CR	CR	4	4	No change	100	100
Dypsis lantzeana	VU	VU	12141	2925	No change	50	70
Dypsis lanuginosa	CR	EW	18	18	Downlisted	50	50
Dypsis lastelliana	LC	NotT	72396	2340	No change	50	60
Dypsis leptocheilos	CR	DD	4	4	Not comparable	0	0
Dypsis ligulata	DD	EW	–	–	Not comparable	–	–
Dypsis linearis	EN	EW	153	96	Downlisted	50	50
Dypsis lokohoensis	VU	VU	6506	600	No change	40	100
Dypsis loucoubensis	CR	EN	367	100	Uplisted	100	100
Dypsis louvelii	VU	VU	8884	612	No change	20	60
Dypsis lucens	DD	EW	–	–	Not comparable	–	–
Dypsis lutea	EN	CR	1435	90	Downlisted	30	30
Dypsis lutescens	NT	NotT	51777	1700	Uplisted	20	20
Dypsis madagascariensis	LC	Rare	115274	5175	Not comparable	30	40
Dypsis mahia	CR	CR	4	4	No change	100	100
Dypsis makirae	VU	–	18	12	Described post-1995	0	80
Dypsis malcomberi	EN	VU	615	64	Uplisted	100	100
Dypsis mananjarensis	NT	VU	25568	1200	Downlisted	20	30
Dypsis mangorensis	CR	CR	4000	80	No change	40	40
Dypsis marojejyi	VU	VU	337	21	No change	100	100
Dypsis mcdonaldiana	EN	VU	3835	48–499	Uplisted	40	70
Dypsis metallica	CR	–	4	4	Described post-1995	100	100
Dypsis minuta	VU	VU	127	45	No change	80	80
Dypsis mirabilis	EN	EN	267	102	No change	70	70
Dypsis mocquerysiana	NT	VU	7596	3145	Downlisted	60	70

Table 3. Cont.

Species	2012 Red List Assessment	1995 Red List Assessment	EOO (km^2)	AOO (km^2)	Status change	Populations in protected areas: MNP only (%)	Populations in protected areas: SAPM (%)
Dypsis monostachya	DD	DD	492	–	No change	–	–
Dypsis montana	VU	DD	52	14	Not comparable	100	100
Dypsis moorei	EN	EN	4623	25	No change	50	50
Dypsis nauseosa	CR	CR	4295	256	No change	0	50
Dypsis nodifera	LC	NotT	162112	6400	No change	50	80
Dypsis nossibensis	CR	CR	4	4	No change	100	100
Dypsis occidentalis	VU	DD	9567	600	Not comparable	60	60
Dypsis onilahensis	VU	VU	225319	4950	No change	40	40
Dypsis oreophila	VU	VU	19830	1000	No change	30	80
Dypsis oropedionis	CR	CR	5431	120	No change	30	30
Dypsis ovobontsira	CR	CR	4	4	No change	100	100
Dypsis pachyramea	LC	VU	883	279	Downlisted	70	70
Dypsis paludosa	VU	VU	19094	1452	No change	40	70
Dypsis perrieri	VU	VU	23202	540	No change	60	80
Dypsis pervillei	CR	EW	2892	4	Not comparable	30	30
Dypsis pilulifera	VU	VU	68666	704	No change	60	90
Dypsis pinnatifrons	LC	NotT	250579	6000	No change	30	80
Dypsis plumosa	DD	–	–	–	Described post-1995	–	–
Dypsis plurisecta	DD	EW	–	–	Not comparable	–	–
Dypsis poivreana	EN	CR	289	30	Downlisted	0	100
Dypsis prestoniana	VU	VU	15208	400	No change	30	80
Dypsis procera	VU	VU	18576	756	No change	40	70
Dypsis procumbens	NT	NotT	161478	5746	Uplisted	50	70
Dypsis psammophila	EN	CR	4234	112	Downlisted	0	90
Dypsis pulchella	CR	EW	11766	147	Not comparable	0	0
Dypsis pumila	CR	VU	4	4	Uplisted	100	100
Dypsis pusilla	VU	VU	2212	342	No change	100	100
Dypsis rakotonasoloi	CR	–	6	4	Described post-1995	0	100
Dypsis ramentacea	CR	CR	4	4	No change	100	100
Dypsis reflexa	CR	–	6	4	Described post-1995	100	100
Dypsis remotiflora	CR	EW	5045	14	Not comparable	50	50
Dypsis rivularis	EN	VU	16789	457	Uplisted	60	60
Dypsis robusta	CR	–	4	4	Described post-1995	0	0
Dypsis sahanofensis	CR	EN	16653	45	Uplisted	0	0
Dypsis saintelucei	EN	CR	22453	210	Downlisted	0	80

Table 3. Cont.

Species	2012 Red List Assessment	1995 Red List Assessment	EOO (km^2)	AOO (km^2)	Status change	Populations in protected areas: MNP only (%)	Populations in protected areas: SAPM (%)
Dypsis sancta	CR	–	4	4	Described post-1995	100	100
Dypsis sanctaemariae	CR	CR	7	7	No change	0	0
Dypsis scandens	CR	CR	15	7	No change	0	0
Dypsis schatzii	EN	VU	108	18	Uplisted	100	100
Dypsis scottiana	VU	VU	7612	1529	No change	40	40
Dypsis serpentina	VU	VU	901	216	No change	40	80
Dypsis simianensis	EN	EN	25806	340	No change	40	70
Dypsis singularis	CR	CR	19	4	No change	50	50
Dypsis soanieranae	DD	EW	–	–	Not comparable	–	–
Dypsis spicata	LC	Rare	24904	1300	Not comparable	40	70
Dypsis tanalensis	CR	EW	8	8	Not comparable	0	0
Dypsis tenuissima	EN	EN	1242	64	No change	50	100
Dypsis thermarum	VU	Rare	77	72	Not comparable	80	100
Dypsis thiryana	VU	Rare	62521	1245	Not comparable	60	70
Dypsis thouarsiana	DD	DD	–	–	No change	–	–
Dypsis tokoravina	CR	EN	341	97	Uplisted	70	100
Dypsis trapezoidea	CR	CR	4	4	No change	0	0
Dypsis tsaratananensis	DD	DD	8	–	No change	–	–
Dypsis tsaravoasira	VU	EN	40289	891	Downlisted	70	80
Dypsis turkii	EN	–	1602	462	Described post-1995	70	70
Dypsis utilis	EN	VU	11592	440	Uplisted	70	90
Dypsis viridis	VU	VU	6893	962	No change	60	80
Dypsis vonitrandambo	CR	–	8	8	Described post-1995	100	100
Lemurophoenix halleuxii	EN	EN	1729	31	No change	50	70
Marojejya darianii	EN	CR	11080	80	Downlisted	50	80
Marojejya insignis	LC	VU	91513	2710	Downlisted	60	70
Masoala kona	EN	EN	693	36	No change	0	30
Masoala madagascariensis	CR	VU	15803	77	Uplisted	40	80
Orania longisquama	LC	Rare	151841	2345	Not comparable	30	80
Orania ravaka	VU	VU	8913	220	No change	70	80
Orania trispatha	VU	CR	25198	1644	Downlisted	70	90
Ravenea albicans	EN	EN	19384	929	No change	80	90
Ravenea beentjei	CR	–	7	5	Described post-1995	0	100
Ravenea delicatula	CR	–	6	4	Described post-1995	0	0
Ravenea dransfieldii	EN	VU	37979	1856	Uplisted	80	90

Table 3. Cont.

Species	2012 Red List Assessment	1995 Red List Assessment	EOO (km^2)	AOO (km^2)	Status change	Populations in protected areas: MNP only (%)	Populations in protected areas: SAPM (%)
Ravenea glauca	VU	VU	9989	443	No change	100	100
Ravenea hypoleuca	CR	–	575	8	Described post-1995	0	0
Ravenea julietiae	EN	EN	34734	112	No change	40	80
Ravenea krociana	EN	VU	10241	450	Uplisted	70	70
Ravenea lakatra	VU	VU	44	9	No change	40	70
Ravenea latisecta	CR	EN	44	9	Uplisted	50	100
Ravenea louvelii	CR	EN	9	4	Uplisted	80	80
Ravenea madagascariensis	LC	Rare	137043	45300	Not comparable	60	70
Ravenea musicalis	VU	VU	4	4	No change	0	0
Ravenea nana	EN	EN	75260	220	No change	40	40
Ravenea rivularis	EN	VU	2122	144	Uplisted	20	20
Ravenea robustior	NT	Rare	312828	2200	Not comparable	60	70
Ravenea sambiranensis	LC	VU	355990	52360	Downlisted	60	60
Ravenea xerophila	VU	EN	17191	676	Downlisted	30	40
Satranala decussilvae	EN	EN	3248	86	No change	50	80
Tahina spectabilis	CR	–	4	4	Described post-1995	0	0
Voanioala gerardii	CR	CR	264	12	No change	60	80

Where available, both the 1995 and 2012 conservation assessments are given, along with EOO (extent of occurrence) and AOO (area of occupancy) from the 2012 assessment; see methods for details. The percentage of populations (geographically distinct groups [30]) recorded inside the MNP and SAPM protected area networks is also given for each species (note that the expanded SAPM network includes MNP). IUCN Red List categories: Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), Data Deficient (DD) [30]; two additional ratings were used in the 1995 assessment [10], Not Threatened (NotT) and Rare.

doi:10.1371/journal.pone.0103684.t003

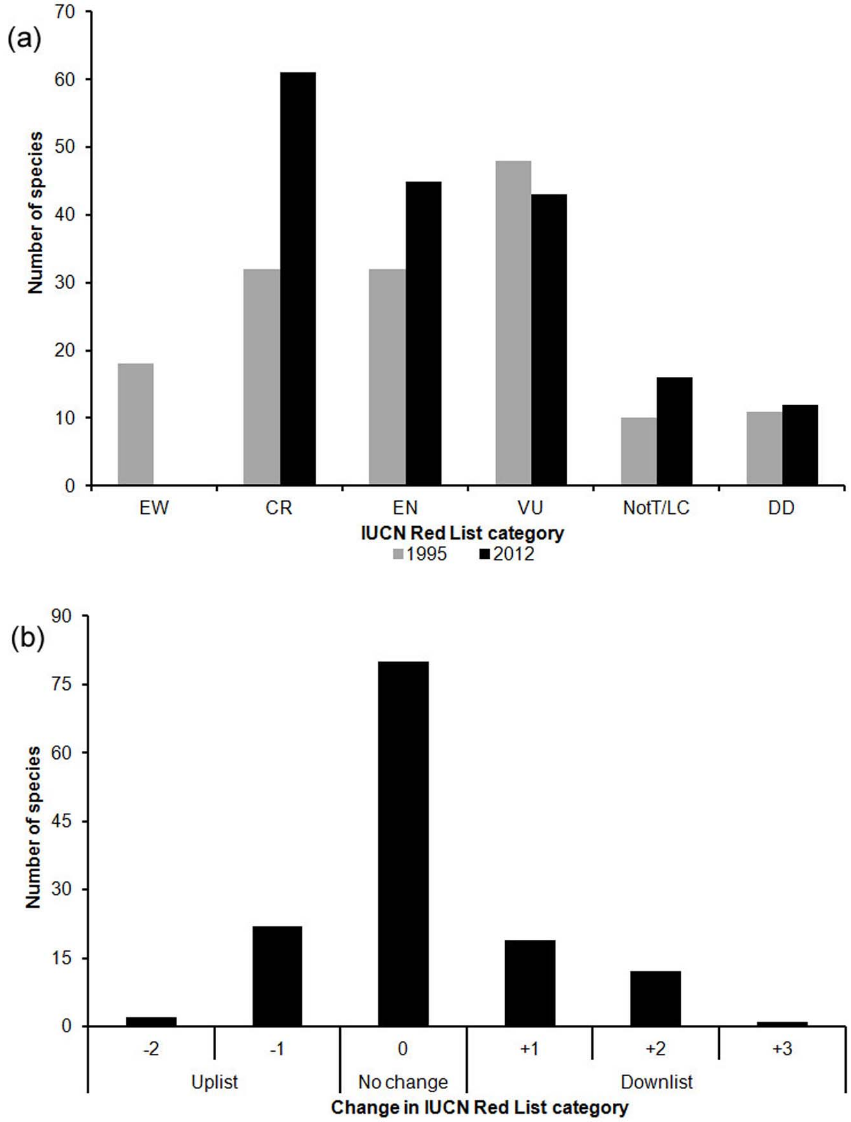


Figure 3. Comparison between the palm assessment of 1995 and 2012. IUCN Red List categories: Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Least Concern (LC), Data Deficient (DD) [31]. (a) Number of species assessed in each category (total assessments: 164 in 1995, 192 in 2012). All species assessed in each year are illustrated (see Table 3), except for those placed in categories that are not comparable (13 species assessed as "Rare" in 1995 [10] and 14 species assessed as NT in 2012 [44]; see methods). (b) Change in IUCN Red List status (see Table 3) where positive values indicate downlisting to lower extinction risk (e.g. CR to EN is a downlisting of 1 step) and negative values indicate uplisting to higher extinction risk (e.g. EN to CR is an uplisting of 1 step). Figure 3b includes 130 data sufficient species (i.e. excluding species rated as DD in either year) that were assessed in comparable categories in both 1995 [10] and 2012 [44].
doi:10.1371/journal.pone.0103684.g003

comparable in both the 1995 assessment and the 2012 assessments (i.e. excluding NT and "Rare"). Numbers of species assessed as DD, LC and VU were similar in both assessments (11, 10 and 48 in 1995, 13, 16 and 43 in 2012, respectively; Fig. 3a). In contrast, numbers of species assessed as EN and CR were much higher in 2012 than 1995 (32 and 32 in 1995, 45 and 61 in 2012, respectively; Fig. 3a). There are two main reasons for this. Firstly, all 18 species assessed as EW in 1995 were assigned to other categories in 2012 based on additional information, the majority being rated as EN or CR. Five of the 18 species were assessed as DD, but insufficient evidence was found to rate any species as EW in the 2012 assessment. Secondly, 28 species were discovered and described after 1995 and were thus assessed for the first time in 2012. Of these species, only *Dypsis ankirindro* (NT) is not regarded as threatened while the remainder are most being classified as CR (18 species). These newly discovered species are mostly known only from a single site where area of occupancy (AOO) is often low ($<$ 4 km^2, e.g. *Dypsis andilamenensis*, *D. gronophyllum*, *Tahina spectabilis*) and known population sizes are small, some with less than 10 mature individuals recorded in the wild (e.g. *Dypsis humilis*, *D. robusta*).

Comparison of the classes of change between 1995 and 2012 reveals a contrasting pattern (Fig. 3b). Of the 130 species evaluated in both years with data sufficient, comparable assessments, most (80) species showed no change in status and more species were downlisted than uplisted. Specifically, 32 species moved from EW to CR, EN or VU, CR to EN or VU, and EN to VU or NT, and 24 species moved from EN to CR, VU to EN or

Table 4. Threatened and data deficient palm species that do not occur in the SAPM protected area network.

Species	Location	Major threats
Beccariophoenix alfredii (VU)	Betafo	Fires, harvest of seeds for horticulture
Dypsis andilamenensis (CR)	Andilamena	Habitat loss due to mining and agriculture
Dypsis ankaizinensis (DD)	Tsaratanana	Unknown
Dypsis aquatilis (CR)	Fort-Dauphin	Fire, habitat loss due to mining and agriculture
Dypsis basilonga (EN)	Andrambovato and Vatovavy	Habitat loss due agriculture, harvest of seeds for horticulture, harvest of palm heart
Dypsis canescens (DD)	Ambilobe	Unknown
Dypsis commersoniana (DD)	Fort-Dauphin	Unknown
Dypsis dracaenoides (CR)	Vondrozo	Habitat loss due to logging and agriculture
Dypsis gronophyllum (CR)	Vondrozo	Habitat loss due to logging and agriculture
Dypsis henricii (DD)	Fort-Dauphin	Unknown
Dypsis heteromorpha (DD)	Tsaratanana	Unknown
Dypsis humilis (CR)	Ambodivoahangy (Makira)	Habitat loss due to logging and agriculture
Dypsis ifanadianae (CR)	Ifanadiana	Habitat loss due to logging and agriculture, harvest of seeds for horticulture
Dypsis leptocheilos (CR)	Maevatanana	Habitat loss due to agriculture, harvest of seeds for horticulture
Dypsis ligulata (DD)	Ambilobe	Unknown
Dypsis monostachya (DD)	Maroantsetra	Unknown
Dypsis plurisecta (DD)	Maroantsetra	Unknown
Dypsis pulchella (CR)	Andilamena	Habitat loss due to mining, logging and agriculture
Dypsis robusta (CR)	Ifanadiana	Habitat loss due to agriculture
Dypsis sahanofensis (CR)	Ambositra, Anosibe an'Ala and Vatovavy	Habitat loss due to logging and agriculture
Dypsis sanctaemariae (CR)	Sainte Marie	Habitat loss due to logging and agriculture
Dypsis scandens (CR)	Ifanadiana	Habitat loss due to logging and agriculture, harvest of stems for weaving
Dypsis soanieranae (DD)	Soanierana Ivongo	Unknown
Dypsis tanalensis (CR)	Vondrozo	Habitat loss due to logging and agriculture
Dypsis trapezoidea (CR)	Vatovavy	Habitat loss due to logging and agriculture
Ravenea delicatula (CR)	Andilamena	Habitat loss due to mining, logging and agriculture
Ravenea musicalis (CR)	Fort-Dauphin	Harvest of seeds for horticulture, harvest of stems to make canoes
Tahina spectabilis (CR)	Analalava (Mahajanga)	Fire, grazing by livestock

Three remaining data deficient species are not listed here as their distributions are unknown (Dypsis lucens, D. plumosa and D. thouarsiana). Some of the locations listed here are close to protected areas (e.g. Tsaratanana, Vondrozo), but the known palm localities fall outside the protected areas boundaries.
doi:10.1371/journal.pone.0103684.t004

CR, and NotT to NT. The downlisting of species is primarily due to increased knowledge of palm distributions and populations, rather than an actual change in their threat status in the wild. Changes in status may also be partly due to criteria being more rigorously applied in 2012. However, deforestation and over-exploitation of some species has resulted in the genuine decline of populations or even to local extinction (e.g. *Dypsis ambositrae*, *D. ifanadianae* and *Voanioala gerardii*), and has resulted in genuine uplisting of these taxa.

Protected area coverage

The expansion of protected areas in Madagascar from the older MNP network to the new SAPM network is highly beneficial to palms. Under the MNP network, 56 species were not included in protected areas. The SAPM network protects at least one population of all but 28 species, a significant improvement over the MNP Network (Tables 3 and 4). Moreover, the SAPM network protects many additional populations of threatened palm species that were not protected by the MNP network. In total, the protected area coverage of populations of 77 threatened species is increased, with an average of 42% more populations being protected under the SAPM network than MNP for these species (Table 3).

Comparison of IUCN Red List assessments with species presence in protected areas (Fig. 4) demonstrates that species known only from outside the SAPM network are either threatened or DD (Table 4). All have small range sizes, many persist in degraded habitats and some have not been seen in the wild for several decades. The majority of the unprotected, threatened species are assessed as CR, e.g. *Dypsis ifanadianae*, *D. scandens* and *Ravenea musicalis*. Some occur in forested areas unconnected to the protected area network (e.g. Ambilobe, Ifanadiana, Vatovavy), whereas others occur in forest adjacent to protected area boundaries (e.g. Andilamena, Tsaratanana, Vondrozo).

Of the species that are protected within the SAPM network, 37 have been recorded in only one protected area while 124 have been documented in two or more protected areas (Fig. 4). The most important protected areas for palms are Masoala, Makira (both 43 species) and Mananara Avaratra (41 species). Marojejy, the Fandriana-Vondrozo Corridor, Manompana, Betampona and Mangerivola each contain more than 20 species. It is significant that three of these eight palm hotspots are newly designated protected areas (the Fandriana-Vondrozo Corridor, Makira,

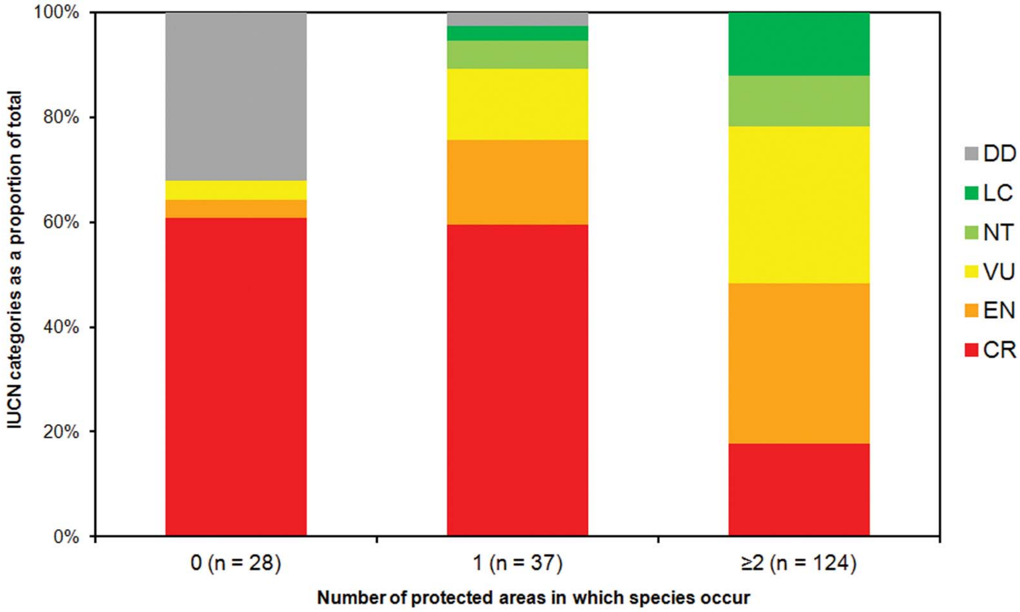


Figure 4. IUCN conservation status of palm species summarised by occurrence in protected areas (SAPM network). Of the 192 assessed species [44], 28 are not recorded from any protected area (coded as 0 in the figure), 37 species are recorded only from one protected area (coded as 1) and 124 species occur in two or more protected areas (coded as ≥2). Three data deficient species are not included as their distributions are unknown (Dypsis lucens, D. plumosa and D. thouarsiana).
doi:10.1371/journal.pone.0103684.g004

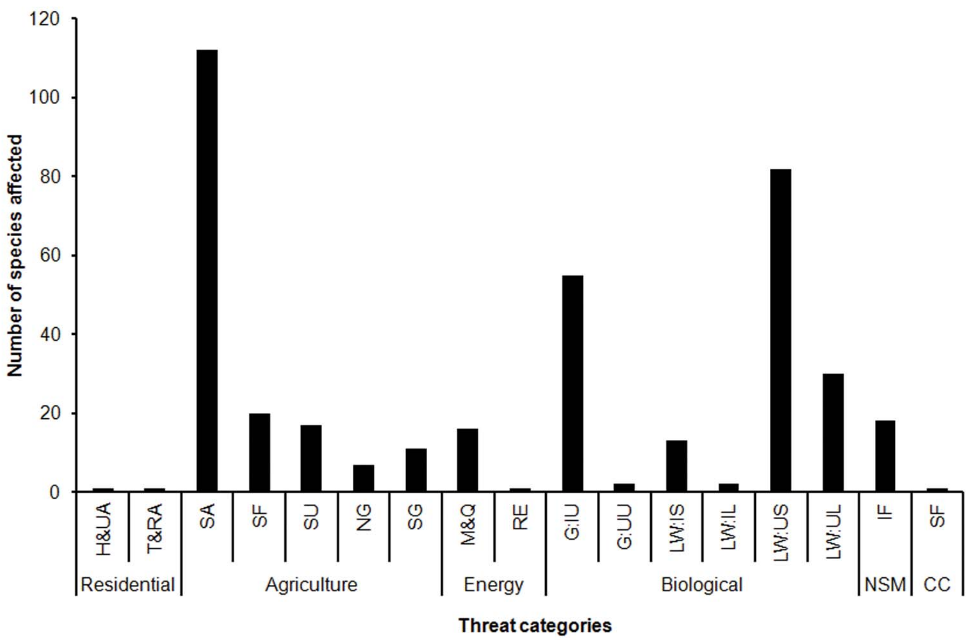


Figure 5. Major threats affecting endemic palm species in Madagascar. Bar heights reflect number of species affected by each threat, as indicated in the 2012 IUCN conservation assessment [44]. Threat categories follow the Threats Classification Scheme version 3.2 [51], using the top two levels of the hierarchy. Abbreviations: Residential & commercial development (Residential): Housing & urban areas (H&UA), Tourism & recreation areas (T&RA); Agriculture & aquaculture (Agriculture): Shifting agriculture (SA), Small-holder farming (SF), Scale unknown/unrecorded (SU), Nomadic grazing (NG), Small-holder grazing, ranching or farming (SG); Energy production & mining (Energy): Mining & quarrying (M&Q), Renewable energy (RE); Biological resource use (Biological): Gathering terrestrial plants, Intentional use (species being assessed is the target) (G:IU), Gathering terrestrial plants, unintentional use (G:UU), Logging & wood harvesting for subsistence, Intentional use: subsistence/small scale (species being assessed is the target) (LW: IS), Logging & wood harvesting, Intentional use: large scale (species being assessed is the target) (LW: IL); Logging & wood harvesting, Unintentional effects: subsistence/small scale (species being assessed is not the target) (LW: US), Logging & wood harvesting, Unintentional effects: large scale (species being assessed is not the target) (LW: UL); Natural system modifications (NSM): Increase in fire frequency (IF); Climate change & severe weather (Climate): Storm & flooding (SF).
doi:10.1371/journal.pone.0103684.g005

Figure 6. Example of palm species under threat in Madagascar. (a) Anthropogenic fires in grasslands, causing decline and destruction of palm populations, such as *Dypsis decipiens* (VU), Itremo. (b) Forest clearance for slash and burn cultivation by smallholder farmers, causing habitat loss for many species, such as *Masoala kona* (EN), Ifanadiana. (c) Gathering of young leaves of *Ravenea lakatra* (VU) for production of woven hats and basketry, Masoala. (d) Destructive harvest of palm heart threatens many species such as *Dypsis saintelucei* (EN), Sainte Luce. (e) Remnant populations of species such as *Tahina spectabilis* (CR), Analalava, near Mahajanga in vegetation remnants isolated within anthropogenic landscapes, at risk from fire, grazing and other human pressures. Image credits: (a) M Rakotoarinivo, (b) WJ Baker, (c, d & e) J Dransfield.
doi:10.1371/journal.pone.0103684.g006

Manompana), further emphasising the importance of the expanded SAPM network. These protected areas vary widely in extent, but all are located in the humid forested east. Nevertheless, protected areas do not guarantee low extinction risk as the majority of species that occur in protected areas are still assessed as threatened (Fig. 4), indicating that threatening processes persist in these areas.

Threats

The major threatening processes for palms in Madagascar are agriculture and biological resource use with 167 and 184 species affected by these threats respectively. More specifically the threats to palm habitats from agriculture relate to annual and perennial non-timber crop production i.e. crops planted for food, fodder, fibre, fuel or other uses, with 'shifting agriculture' listed as the scale of farming affecting the highest number of species (112) (Figs. 5 and 6; threat wordings according to IUCN Threats Classification Scheme (version 3.2) [51]). The threat from biological resource use is related to the gathering of terrestrial plants (55 species, e.g. for palm heart consumption) and logging and wood harvesting (127 species). More specifically the highest scoring threat is from logging and wood harvesting for subsistence on a large scale where the species of palm is actually not intended target, but is threatened due to collateral damage (112 species) i.e. the palms are subject to collateral damage. Other less prevalent threats relate to mining, livestock farming, fires, housing and urban development.

Discussion

As of 2013, 684 native plant species from Madagascar (out of an estimated total of ca. 13,000 [55]) were completely assessed under the IUCN categories and criteria [31] and displayed on the website of the Red List [44]. With 192 species and representing nearly 30% of the Madagascar plant species on the Red List, our study of palms is the largest and most complete IUCN conservation assessment of any plant family on the island. Recently, the IUCN Madagascar Plant Specialist Group (Groupe des Spécialistes des Plantes Malgaches, GSPM) [55] assessed ca. 3,000 plant species from 74 families and 285 genera. In addition, full assessments of smaller taxonomic groups have been completed: Pandanaceae (91 species [25]), Sarcolaenaceae (68 species) and Sphaerosepalaceae (20 species) [56], tribe Coleeae of Bignoniaceae (67 species [57]) and the genus *Delonix* (Fabaceae, 11 species; [58]). Unfortunately, none of these groups of assessments has been formally published on the IUCN Red List yet.

Our finding that as many as 83% of palm species are threatened (best estimate) indicates that the Arecaceae is among the organismal groups facing the highest risk of extinction in Madagascar. Moreover, the proportion of threatened palms in Madagascar is almost four times greater than for plants in general, estimated as 21.5% worldwide [59], and is higher than the estimate for Madagascar's flora as a whole (54%, [60]). At family level, the percentage of threatened species is variable, 49% of all endemic legumes [57], 65% for Sphaerosepalaceae and 75% for Sarcolaenaceae [56], and 81.3% for Pandanaceae [25]. It is notable that the proportions of threatened species in the Arecaceae and Pandanaceae are similar, given that they share functional similarities as woody, often arborescent monocotyledonous plants that are most species rich in humid forests. For major groups of animals in Madagascar, the proportion of threatened species varies widely, for example, 25% for amphibians [61], 37% for reptiles [60] and 94% for lemurs [62].

Comparisons between the 1995 and 2012 assessments of Madagascar palms [10] indicates that downlisting (a movement to a category of lower threat) is more frequent than uplisting, though 21 of 32 downlisted species still fall into threatened categories. These changes to a lower category come from improved knowledge of species distribution, population size, and taxonomy rather than any genuine decline of extinction risk in the wild. In contrast, almost all of our recently discovered species (species not known to science in 1995) are threatened as they typically have small range sizes and are at risk of habitat loss and direct or indirect threats from human pressure [63]. The role of the taxonomist in conservation assessment cannot be overstated as collections-based research and knowledge both in the field and in the herbarium or museum is essential for confirming the identity of species and the distribution of their wild populations. Conservation assessment in the absence of robust taxonomy will result in inaccurate ratings and a tendency to categorise species as DD [57,64]. In our case, intensive taxonomic research and field surveys in Madagascar fundamentally underpin our conservation assessments and have led to the rediscovery of species previously thought to be extinct, as well as the discovery of new populations of threatened species and species new to science.

Our analysis of threats facing palms suggests that the dependency of rural people on forested lands for shifting cultivation and their continued unsustainable exploitation of wild forest products such as palms are key drivers of palm extinction risk. This applies even in remote areas where human population density is low [35]. Our analysis also reveals a novel and insidious threat to palms through the logging or harvesting of other plants at a subsistence level that causes collateral damage to palms. Unless the economic circumstances of rural communities change radically, forest resources such as palms will continue to be exploited unsustainably for basic subsistence needs. Economic factors are a primary concern for the conservation of Madagascar palms, as they are for so many other organisms globally.

Time-delayed biodiversity loss [65] is an important consideration for Madagascar palms as many species persist locally as seedlings or juvenile plants after mature trees have been cleared with the forest. Species in decline may survive for a long time before they become extinct if a threshold in the habitat quality is maintained [66]. Without adequate protection and management, these sites are likely to be lost in the future as disturbance and fragmentation provide suitable habitat for invasive secondary species [12], which have negative impacts on native species by depressing the growth rate at various stages of the life cycle [67].

The high degree of extinction risk faced by Madagascar palms calls into question the effectiveness of previous conservation actions on the island. In a period when human population density and pressure on biodiversity are increasing, the long-term success of protected areas is at the heart of potential solutions for palm conservation. By covering 70% of the remaining humid forest in Madagascar [68], the SAPM network is expected to be considerably more effective for species protection in Madagascar compared with the previous, more limited MNP network, as the new set of reserves has been selected to include narrow range taxa [69]. Our analysis demonstrates that SAPM protects threatened palm populations much more effectively than the MNP network. Nevertheless, the SAPM network has limitations. To date, only Makira has been accorded definitive protected area status, whereas the remainder are not yet formally designated [23]. Consequently, critical protection of the forest and its biodiversity is lacking in the majority of the SAPM network.

Moreover, SAPM does not provide complete protection for Madagascar palms as several priority sites (Table 4), typically forest fragments far from protected areas, are not included. Small areas of intact habitat need to be taken into account as they often contain remnant populations of rare and endemic species [70] that are highly susceptible to environmental stochasticity and local extinction [71]. For example, a monotypic genus of massive fan palm, *Tahina spectabilis*, discovered only in 2006 [72], persists in a 160×50 m patch of forested tsingy (karst limestone) surrounded by anthropogenic grassland near Mahajanga. The protection of this forest is an urgent priority to conserve this isolated, endemic lineage. Some small fragments are included in the SAPM network, such as a ca. 2 km^2 tract of degraded coastal plain forest at Analalava (near Foulpointe), north of Toamasina, which is an outstanding palm hotspot containing 25 palm species, including one local endemic and three species known from only one other site each. This small fragment is managed locally by the Missouri Botanical Garden staff who promote the site for ecotourism [73].

Madagascar palms face exceptional levels of extinction risk by both national and global standards. The conservation of keystone species such as palms [9] is of particular importance due to the potential consequences of their extinction to other species. Humans are among the organisms that rely substantially on ecosystem services provided by palms [10,15,74,75]. The engagement of local communities in conservation initiatives will be critical to their success. Given the intensifying pressure from growing human populations, compounded by projected impacts of climate change on species extinction [76], there is now an urgent need for prioritised action for Madagascar palms. The rigorous IUCN conservation assessment described here provides an essential foundation for such a process.

Acknowledgments

We thank Craig Hilton-Taylor and Henk Beentje for their support and advice during the Red Listing process, and Charlotte Rajeriarison and

Stuart Cable for supervision. We acknowledge the cooperation of the IUCN SSC Madagascar Plant Specialist Group, particularly Sylvie Andriambololonera. Martin Callmander and Pete Lowry provided many useful comments on an earlier draft of the manuscript. We are grateful to the many authorities, institutions and individuals who have supported and facilitated our fieldwork.

Author Contributions

Conceived and designed the experiments: MR JD SPB JM WJB. Performed the experiments: MR JD SPB JM WJB. Analyzed the data: MR JD SPB JM WJB. Contributed reagents/materials/analysis tools: MR JD SPB JM WJB. Wrote the paper: MR JD SPB JM WJB.

References

1. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GA, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403: 853–858. doi:10.1038/35002501.
2. Goodman SM, Benstead JP (2005) Updated estimates of biotic diversity and endemism for Madagascar. Oryx 39: 73–77 doi: 10.1017/S0030605305000128.
3. Harper GJ, Steininger MK, Tucker CJ, Hawkins F (2007) Fifty years of deforestation and forest fragmentation in Madagascar. Environ Conserv 34: 325–333. doi: 10.1017/S0376892907004262.
4. Allnutt TF, Asner GP, Golden CD, Powell GV (2013) Mapping recent deforestation and forest disturbance in northeastern Madagascar. Trop Conserv Sci 6: 1–15.
5. Govaerts R, Dransfield J, Zona SF, Hodel DR, Henderson A (2012) World Checklist of Arecaceae. Facilitated by the Royal Botanic Gardens, Kew. Available: http://apps.kew.org/wcsp/. Accessed 12 June 2013.
6. Rakotoarinivo M, Blach-Overgaard A, Baker WJ, Dransfield J, Moat J, et al. (2013) Palaeo-precipitation determines palm diversity across Madagascar - a tropical biodiversity hotspot. Proc R Soc Lond B Biol Sci 280: 20123048. doi:10.1098/rspb.2012.3048.
7. Kissling WD, Eiserhardt WL, Baker WJ, Borchsenius F, Couvreur TLP, et al. (2012) Cenozoic imprints on the phylogenetic structure of palm species assemblages worldwide. Proc Natl Acad Sci USA 109: 7379–7384. doi:10.1073/pnas.1120467109.
8. Couvreur T, Forest F, Baker W (2011) Origin and global diversification patterns of tropical rain forests: inferences from a complete genus-level phylogeny of palms. BMC Biol 9: 44. doi:10.1186/1741-7007-9-44.
9. Couvreur T, Baker W (2013) Tropical rain forest evolution: palms as a model group. BMC Biol 11: 48. doi:10.1186/1741–7007–11–48.
10. Dransfield J, Beentje H (1995) The palms of Madagascar. The Royal Botanic Gardens, Kew and The International Palm Society. 475 p.
11. Fleischmann K, Edwards PJ, Ramseier D, Kollmann J (2005) Stand structure, species diversity and regeneration of an endemic palm forest on the Seychelles. Afr J Ecol 43: 291–301. doi: 10.1111/j.1365–2028.2005.00567.x.
12. Scariot A (1999) Forest fragmentation effects on palm diversity in central Amazonia. J Ecol 87: 66–76. doi: 10.1046/j.1365–2745.1999.00332.x.
13. Moat J, Smith P (2007) Atlas of the Vegetation of Madagascar. Kew Publishing. 124p.
14. Bennett BC (2011) Twenty-five economically important plant families. Encyclopedia of Life Support. Available: http://www.eolss.net/sample-chapters/c09/e6-118-03.pdf. Accessed 15May 2013.
15. Dransfield J, Uhl NW, Asmussen CB, Baker WJ, Harley MM, et al. (2008) Genera Palmarum – the evolution and classification of palms. Kew Publishing. 744 p.
16. Dransfield J (1999) Madagascar as a source of new palm introductions. Acta Hortic 486: 21–32.
17. Isaac NJ, Turvey ST, Collen B, Waterman C, Baillie JE (2007) Mammals on the EDGE: Conservation priorities based on threat and phylogeny. PLoS ONE 2: e296. doi:10.1371/journal.pone.0000296.
18. Richard D, Evans D (2006) The need for plant taxonomy in setting priorities for designated areas and conservation management plans: a European perspective. In: Leadlay E, Jury S, editors. Taxonomy and Plant conservation. Cambridge University Press. pp. 163–176.
19. Bruner AG, Gullison RE, Rice RE, da Fonseca GA (2001) Effectiveness of parks in protecting tropical biodiversity. Science 291: 125–128. doi: 10.1126/science.291.5501.125.
20. Borrini-feyerabend G, Dudley N(2005) Les Aires Protégées à Madagascar : bâtir le système à partir de la base. World Commission on Protected Areas & International Union for Conservation of Nature. 51 p.
21. Norris S (2006) Madagascar defiant. BioScience 56: 960–960. doi:10.1641/0006–3568(2006)56[960:MD]2.0.CO;2.
22. Mittermeier RA, Hawkins F, Rajaobelina S, Langrand O (2005) Wilderness conservation in a biodiversity hotspot. International Journal of Wilderness 11: 42–45.
23. Système des Aires Protégées de Madagascar [SAPM] (2011) Atlas numerique du SAPM. Available : http://atlas.rebioma.net/index.php?option = com_wrapper&Itemid = 39. Accessed 3 June 2013.
24. Nicoll ME (2003) Forests outside protected areas In: Goodman SM, Benstead JP, editors. The Natural History of Madagascar. University of Chicago Press. pp. 1432–1437.
25. Callmander MW, Schatz GE, Lowry II PP, Laivao MO, Raharimampionona J, et al. (2007) Identification of priority areas for plant conservation in Madagascar using Red List criteria: rare and threatened Pandanaceae indicate sites in need of protection. Oryx 41: 168–176. doi: 10.1017/S0030605307001731.
26. Rodrigues ASL, Pilgrim JD, Lamoreux JF, Hoffmann M, Brooks TM (2006) The value of the IUCN Red List for conservation. Trends Ecol Evol 21: 71–76. doi:10.1016/j.tree.2005.10.010.
27. Mace G, Collar N, Gaston K, Hilton-Taylor C, Akçakaya R, et al. (2008) Quantification of extinction risk: IUCN's system for classifying threatened species. Conserv Biol 22: 1424–1442. doi: 10.1111/j.1523–1739.2008.01044.x.
28. Vié JC, Hilton-Taylor C, Pollock C, Ragle J, Smart J, et al. (2008) The IUCN Red List: a key conservation tool. IUCN, Switzerland. 13 p.
29. International Union for Conservation of Nature [IUCN] (1994) IUCN Red List Categories and Criteria version 2.3. Available: http://www.iucnredlist.org/technical-documents/categories-and-criteria/1994-categories-criteria. Accessed 29 May 2013.
30. International Union for Conservation of Nature [IUCN] (1998) 1997 IUCN Red List of Threatened Plants. World Commission on Protected Areas [WCMC] & International Union for Conservation of Nature [IUCN]. 862 p.
31. International Union for Conservation of Nature [IUCN] (2001) IUCN Red List Categories and Criteria: Version 3.1. IUCN, Gland, Switzerland and Cambridge, UK. 30 p.
32. Dransfield J, Beentje H, Britt A, Ranarivelo T, Razafitsalama J (2006) Field guide to the palms of Madagascar. Royal Botanic Gardens, Kew. 172 p.
33. Rakotoarinivo M, Trudgen MS, Baker WJ (2009) The palms of Makira protected areas. Palms 53: 125–146.
34. Rakotoarinivo M, Dransfield J (2010) New species of Dypsis and Ravenea (Arecaceae) from Madagascar. Kew Bull 65: 279–303.
35. Foibe Taosarintanin'i Madagasikara [FTM] (2006) Madagasikara et ses 22 régions. FTM. 24 p.
36. Battistini R (1996) Paléogéographie et variété des milieux naturels à Madagascar et dans les îles voisines : quelques données de base pour l'étude biogéographique de la région malgache. In: Lourenço WR, editor. Biogéographie de Madagascar, ORSTOM, Paris. pp. 1–17.
37. Jury MR (2003) The Climate of Madagascar. In: Goodman SM, Benstead JP, editors. The Natural History of Madagascar. University of Chicago Press. pp. 75–87.
38. WorldBank (2013) Population density. Available: http://data.worldbank.org/country/madagascar. Accessed 31 May 2013.
39. Allnutt TF, Ferrier S, Manion G, Powell GVN, Ricketts TH, et al. (2008) A method for quantifying biodiversity loss and its application to a 50-year record of deforestation across Madagascar. Cons Lett 1: 173–181. doi: 10.1111/j.1755–263X.2008.00027.x.
40. Thiers B (2012) Index Herbariorum, a global directory of public herbaria and associated staff. New York Botanical Garden's virtual herbarium. Available: http://sweetgum.nybg.org/ih/. Accessed 26 April 2013.
41. Schatz G, Lescot M (2003) Gazetteer to Malagasy Botanical Collecting Localities. Missouri Botanical Garden Available: http://www.mobot.org/MOBOT/Research/madagascar/gazetteer/. Accessed 15 July 2012.
42. Google (2010) Google Earth (version 5.2.1.1588). Available: http://www.google.com/earth/explore/products/. Accessed 03 November 2011.
43. International Union for Conservation of Nature [IUCN] Standards and Petitions Subcommittee (2011) Guidelines for Using the IUCN Red List Categories and Criteria. Version 9.0. Prepared by the Standards and Petitions Subcommittee. Available : http://www.iucnredlist.org/documents/RedListGuidelines.pdf. Accessed: 06 July 2013.
44. IUCN (2012) IUCN Red List of Threatened Species. Version 2013.1. Available: http://www.iucnredlist.org Accessed 10 October 2013.
45. Gaston KJ, Fuller RA (2009) The sizes of species' geographic ranges. J Appl Ecol 46: 1–9. doi: 10.1111/j.1365–2664.2008.01596.x.
46. Willis F, Moat J, Paton A (2003) Defining a role for herbarium data in Red List assessments : a case study of *Plectranthus* from eastern and southern tropical Africa. Biodivers Conserv 12: 1537–1552. doi: 10.1023/A:1023679329093.
47. Bachman S, Moat J, Hill AW, de la Torre J, Scott B (2011) Supporting Red List threat assessments with GeoCAT: geospatial conservation assessment tool. Zookeys 150: 117–126. doi: 10.3897/zookeys.150.2109.
48. Moat J (2007) Conservation assessment tools extension for ArcView 3.x, version 1.2. GIS Unit, Royal Botanic Gardens, Kew. Available: http://www.rbgkew.org.uk/gis/cats. Accessed 12 November 2012.
49. Humbert H, Cours-Darne G (1965) Notice de la carte de Madagascar : carte internationale du tapis végétal et des conditions écologiques à 1:1.000.000. Institut Français de Pondichéry. 162 p.
50. Association Nationale pour la Gestion des Aires Protégées [ANGAP] (2001) Madagascar Protected Area System Management Plan. Mye. 112 p.
51. International Union for Conservation of Nature [IUCN] (2012) Threats Classification Scheme (Version 3.2). Available: http://www.iucnredlist.org/technical-documents/classification-schemes/ threats-classification-scheme. Accessed 10 May 2013.

52. Hoffmann M, Hilton-Taylor C, Angulo A, Böhm M, Brooks TM, et al. (2010) The Impact of Conservation on the Status of the World's Vertebrates. Science 330: 1503–1509. doi: 10.1126/science.1194442.
53. Butchart SH, Akcakaya HR, Kennedy E, Hilton-Taylor C (2006) Biodiversity indicators based on trends in conservation status: strengths of the IUCN Red List index. Conserv Biol 20: 579–581. doi: 10.1111/j.1523-1739.2006.00410.x.
54. Butchart SH, Resit Akçakaya H, Chanson J, Baillie JE, Collen B, et al. (2007) Improvements to the Red List Index. PLoS ONE 2: e140. doi:10.1371/journal.pone.0000140.
55. Groupe des Spécialistes des Plantes Malgaches [GSPM] (2011) Liste rouge des plantes vasculaires endemiques de Madagascar. Sud Expert Plantes, Antananarivo. 188 p.
56. Ramananjanahary RH, Frasier CL, Lowry II PP, Rajaonary FA, Schatz GE (2010) Madagascar's endemic plant families, species Guide. Missouri Botanical Garden, Madagascar. 150 p.
57. Good TC, Zjhra ML, Kremen C (2006) Addressing data deficiency in classifying extinction risk: a case study of a radiation of Bignoniaceae from Madagascar. Conserv Biol 20: 1099–1110. doi: 10.1111/j.1523–1739.2006.00473.x.
58. Rivers MC, Bachman SP, Meagher TR, Nic Lughadha E, Brummitt NA (2010) Subpopulations, locations and fragmentation: applying IUCN red list criteria to herbarium specimen data. Biodivers Conserv 19: 2071–2085. doi: 10.1007/s10531-010-9826-9.
59. Brummitt N, Bachman S (2010) Plants under pressure a global assessment. The first report of the IUCN Sampled Red List Index for plants. Royal Botanic Gardens, Kew, UK. Available : http://www.kew.org/ucm/groups/public/documents/document/kppcont_082104.pdf. Accessed 14 September 2012.
60. International Union for Conservation of Nature (2013) The IUCN Red List of threatened species - Summary statistics. Available: http://www.iucnredlist.org/documents/summarystatistics/2013_1_RL_Stats_Table_5.pdf. Accessed 25 October 2013.
61. Andreone F, Cadle JE, Cox N, Glaw F, Nussbaum RA, et al. (2005) Species review of Amphibians extinction risks in Madagascar: conclusions from the global Amphibians assessment. Conserv Biol 19: 1790–1802. doi: 10.1111/j.1523–1739.2005.00249.x.
62. Davies N, Schwitzer C (2013) Lemur conservation status review: an overview of the Lemur Red-Listing results 2012. In: Schwitzer C, Mittermeier RA, Davies N, Johnson S, Ratsimbazafy J, et al., editors. Lemurs of Madagascar: A Strategy for their Conservation 2013–2016. IUCN SSC Primate Specialist Group, Bristol Conservation and Science Foundation, and Conservation International pp. 13–33.
63. Joppa LN, Roberts DL, Myers N, Pimm SL (2011) Biodoversity hotspots house most undiscovered plant species. P Natl Acad Sci USA 108: 13171–13176. doi:10.1073/pnas.1109389108.
64. Callmander MW, Schatz GE, Lowry II PP (2005) UICN Red List assessment and the Global Strategy for plant conservation : taxonomists must act now. Taxon 54: 1047–1050. doi: 10.2307/25065491.
65. Krauss J, Bommarco R, Guardiola M, Heikkinen RK, Helm A, et al. (2010) Habitat fragmentation causes immediate and time-delayed biodiversity loss at different trophic levels. Ecol Lett 13: 597–605. doi: 10.1111/j.1461–0248.2010.01457.x.
66. Fattorini S, Borges PAV (2012) Species-area relationships underestimate extinction rates. Acta Oecol 40: 27–30. doi:10.1038/nature09985.
67. Rojas-Sandoval J, Meléndez-Ackerman E (2012) Effects of an invasive grass on the demography of the Caribbean cactus *Harrisia portoricensis*: Implications for cacti conservation. Acta Oecol 41: 30–38. doi: 10.1016/j.actao.2012.04.004.
68. Hannah L, Dave R, Lowry II PP, Andelman S, Andrianarisata M, et al. (2008) Climate change adaptation for conservation in Madagascar. Biol Letters 4: 590–594. doi:10.1098/rsbl.2008.0270.
69. Kremen C, Cameron A, Moilanen A, Philips SJ, Thomas CD, et al. (2008) Aligning conservation priorities across taxa in Madagascar with high resolution planning tools. Nature 230: 222–226. doi: 10.1126/science.1155193.
70. Marcot BG, Raphael MG, Schumaker NH, Galleher B (2013) How big and how close? habitat patch size and spacing to conserve a threatened species. Nat Resour Model 26: 194–214. doi: 10.1111/J.1939–7445.2012.00134.X.
71. Hobbs RJ (2007) Setting effective and realistic restoration goals: key directions for research. Restor Ecol 15 : 354–357. doi: 10.1111/j.1526-100X.2007.00225.x.
72. Dransfield J, Rakotoarinivo M, Baker WJ, Bayton RP, Fisher JB, et al. (2008). A new Coryphoid palm genus from Madagascar. Bot J Linn Soc 156: 79–91. doi: 10.1111/j.1095-8339.2007.00742.x.
73. Rakotoarinivo M, Razafitsalama JL, Baker W, Dransfield J (2010) Analalava – a palm conservation hotspot in eastern Nadagascar. Palms 54: 141–151.
74. Byg A, Balslev H (2001) Diversity and use of palms in Zahamena, eastern Madagascar. Biodivers Conserv 10: 951–970. doi:10.1023/A:1016640713643.
75. Byg A, Balslev H (2003) Palm heart extraction in Zahamena, Eastern Madagascar. Palms 47: 37–44.
76. Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, et al. (2004) Extinction risk from climate change. Nature 427: 145–148. doi:10.1038/nature02121.

Kew
ROYAL BOTANIC GARDENS

A conservation assessment for all plants

Responding to GSPC target 2 - a conservation assessment triage

Tracking progress in plant conservation assessments

Target 2 of the Global Strategy for Plant Conservation: "**An assessment of the conservation status of all known plant species, as far as possible, to guide conservation action**" has been difficult to monitor as the information is currently stored in disparate sources. Here we present a working list of plant conservation assessments derived from the global IUCN Red List, the National Red List project and literature and other data sources. For the first time we have a baseline of recorded plant threat status against which we can monitor progress. A portal with search options and links back to the original source assessments is planned.

Furthermore, the results of a triage approach to prioritise species for conservation action is presented here.

Cycas thoursii – an threatened plant in Madagascar

Methods

National and regional Red List processes

→ National/ Regional Red List

IUCN Plant Specialist Groups

→ IUCN Red List

Literature – Checklists, floras, journal articles.

→ Kew assessment tracking system

→ **GSPC target 2 working list**

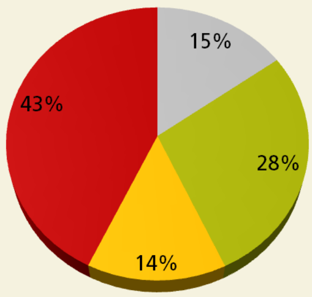
Results

For the first time an interim list of assessments for plants is presented in response to the GSPC target 2. The 2013 interim list shows:

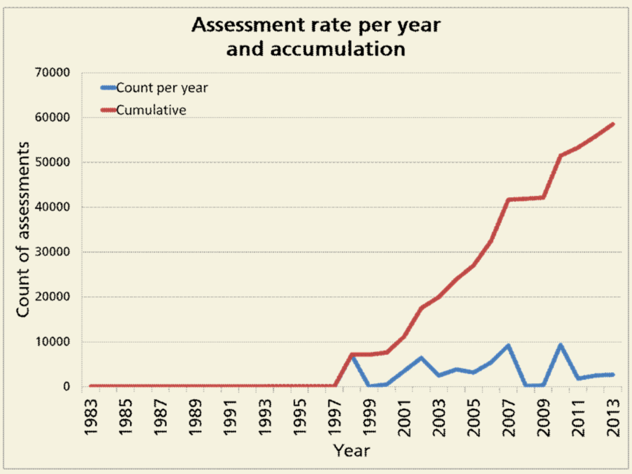
- **58,494** assessments for plants (approx. **16% of all plants**)
- **43%** are categorised as '**Threatened**' indicating high priority for conservation
- More than half (**52%**) of known assessments are at regional/national scale

Global plant triage

(n= 58,494)



It is difficult to estimate the total number of plants that have been assessed and the expected rate of new assessments as this is an interim list that does not yet account for all historical assessments. New assessments will be added to each of the three major data sources and annual updates to this list will likely show a greater coverage of plant assessments ultimately leading to a conservation assessment for all plants.



More information: s.bachman@kew.org | @kewgis | www.kew.org/gis

http://www.iucnredlist.org/ | http://www.nationalredlist.org/

Royal Botanic Gardens, Kew, Richmond, Surrey TW9 3AB, UK Telephone +44 (0)20 8332 5000 www.kew.org

```
#functions.R
#Contains all of the functions needed to perform the actual analysis.
#source()'ing this file should have no side effects other than loading up the
#function definitions. This means that you can modify this file and reload it
#without having to go back an repeat steps 1 & 2 which can take a long time to run for large data sets.

### RedLeast - or new name 'threatAssessR' gather parameters for plant species using GBIF and POWO (distribution, EOO, AOO etc.)
### Compare results with predefined model to determine if species are Least Concern according to IUCN criteria
### For LC species you can generate IUCN SIS point files and SIS csv files for Red List submission of LC species
### Steve Bachman & Justin Moat & Robin Freeman

# other options
options(stringsAsFactors = FALSE)

# install libraries for Red List download
#install.packages("rredlist")

# load libraries for Red List download
library(rredlist)

# 0. RED LIST
# function to get the top level species info based on each ID - WORKING ###
rl.apply = function(x, key){
  sp <- rl_search(id=x,key=rlkey)
  sp = sp$result
  return(sp)
}

# get IDs for all plants on the Red List ###
rl_plant_IDs = function(rlkey){

  # get IDs (all taxa on Red List) from pages of 10,000 and keep going until page has no more species
  i=1
  testcount = 1
  rl = rl_sp(0, key = rlkey)
  rl.all = rl$result

  while ((testcount)>'0'){
    test = rl_sp(i, key = rlkey)
    testcount = test$count
    rl.all = rbind(rl.all,test$result)
    i = i+1
  }
  # filter on plants 'PLANTAE'
  plants <- rl.all[ which(rl.all$kingdom_name=='PLANTAE'),]

  # filter out the first column 'taxon ID'
  plants.id = plants[,1]

  # run through all IDs using lapply
  apply.rl = lapply(plants.id,rl.apply)
  rl_df = as.data.frame(do.call(rbind,apply.rl))
```

```
  #get RL version number
  #version = rl_version(key = rlkey)

  #get date
  #today = Sys.Date()

  #file path
  #filename = paste0("PLANTAE_RL_version_",version,"_run_on_",today)

  return(rl_df)

}

# install libraries for RedLeast
#install.packages("plyr")
#install.packages("tidyverse")
#install.packages("rgbif")
#install.packages("rgdal")
#install.packages("sp")
#install.packages("rCAT")
#install.packages("data.table")
#install.packages("raster")
#install.packages("jsonlite")
#install.packages("tmap")
#install.packages("shiny")
#devtools::install_github("rstudio/crosstalk")

# load relevant libraries for Red Least
library(plyr)
library(tidyverse)
library(rgbif)
library(rgdal)
library(sp)
library(rCAT)
library(data.table)
library(raster)
library(jsonlite)
library(devtools)
library(pryr)
library(ggmap)
library(leaflet)
#library(crosstalk)

############### FUNCTIONS ##############

# get species name from gbif by key
add_names = function(BigKeys){

  tax_name = name_usage(key=BigKeys)
  full_name = tax_name$data$species
}

# error catcher - updates results.table when there are errors
```

```
update.errors = function(result.table, error.species, error.text) {
  if (nrow(error.species) < 1)
  {
    result.table = result.table
  }
  else{
    as.data.frame(error.species)
    error.species$eWarning = error.text
    result = full_join(result.table,
                       error.species,
                       by = "POWO_ID",
                       copy = FALSE)
    tidytable = result %>% unite(Warning, Warning, eWarning, sep = ";")
    tidytable$Warning = gsub('NA', "", tidytable$Warning)
    tidytable$Warning = gsub(';;', "", tidytable$Warning)
    return(tidytable)
  }
}

# 00  - get names from POWO API
# 0.1 - get species names and ID - user supplies family. POWO may fix page size issue later
get.POWO = function(family, pagesize = 24) {
  #get list first
  full_url =  paste(
    "http://powo.science.kew.org/api/1/search?page=0&page.size=",
    pagesize,
    "&f=accepted_names%2Cspecies_f&q=family%3A",
    family,
    sep = ""
  )
  raw.data <- readLines(full_url, warn = "F", encoding = "UTF-8")
  rd <- fromJSON(raw.data)
  pages = rd$totalPages
  last = pages - 1
  list = c(1:last)
  all.results = rd$results
  accepted = all.results$accepted
  author = all.results$author
  name = all.results$name
  url = all.results$url
  results = cbind(accepted, author, name, url, family = family)

  for (l in list) {
    spe_url =  paste(
      "http://powo.science.kew.org/api/1/search?page=",
      l,
      "&page.size=",
      pagesize,
      "&f=accepted_names%2Cspecies_f&q=family%3A",
      family,
      sep = ""
    )
    raw.data <- readLines(spe_url, warn = "F", encoding = "UTF-8")
    rd <- fromJSON(raw.data)
```

```
    all.results = rd$results
    accepted = all.results$accepted
    author = all.results$author
    name = all.results$name
    url = all.results$url
    all.results = cbind(accepted, author, name, url, family = family)
    results = rbind(results, all.results)
  }
  fam.results = as.data.frame(results)
  fam.results = fam.results %>% unite(full_name, name, author, sep = " ")
  fam.results = fam.results %>% separate(url, into = c("base_url", "POWO_ID"), sep = 31)

  return(fam.results)
}

# 0.2 - get names by checkin binomial (note - doesn;t check authors)
# check if name (binomial) is accepted on POWO. ID is the binomial as a list
check.accepted.POWO = function(binomial) {

  #binomial = "Poa annua"

  # use ID full name to search API
  full_url =  paste("http://plantsoftheworldonline.org/api/1/search?q=species:", binomial, sep = "")

  # get raw json data
  raw.data <- readLines(full_url, warn = "F", encoding = "UTF-8")

  # organise
  rd <- fromJSON(raw.data)

  if (length(rd$results) == 0) {
    # add new column to results and call it warning

    accepted = "NA"
    author = ""
    kingdom = ""
    name = ""
    rank  = ""
    #synonymOf = ""
    base_url = ""
    IPNI_ID = ""
    search_name = binomial
    results = data.frame(accepted,author, kingdom, name, rank, base_url, IPNI_ID,search_name)

  } else {

    # make data frame
    results = as.data.frame(rd$results)

    # add original search term
    results$search_name = binomial

    # filter on
    if (nrow(results) >1) {
```

```
      accepted = "FALSE"
      author = ""
      kingdom = ""
      name = ""
      rank  = ""
      #synonymOf = ""
      base_url = ""
      IPNI_ID = ""
      search_name = binomial
      results = data.frame(accepted,author, kingdom, name, rank, base_url, IPNI_ID,search_name)

    } else {

      # PROBLEM HERE - var with no author - replace with blank field?
      if (!"author" %in% colnames(results)) {
        results$author = NA
      }

      # only include these fields - you don't want synonym of
      results = subset(results, select=c(accepted, author, kingdom,name,rank, url, search_name))

      # split url to get url and IPNI_ID
      results = results %>% separate(url, into = c("base_url", "IPNI_ID"), sep = "names:")

      # take out any results where it matched on something that wasn't species
      results = subset(results, rank == "Species")

      # check if
      if (nrow(results) < 1) {
        # add new column to results and call it warning

        accepted = "NA"
        author = ""
        kingdom = ""
        name = ""
        rank  = ""
        #synonymOf = ""
        base_url = ""
        IPNI_ID = ""
        search_name = binomial
        results = data.frame(accepted,author, kingdom, name, rank, base_url, IPNI_ID,search_name)

      }
      # make data frame
      results = as.data.frame(results)
    }

    return(results)

  }
}

# 1 - get gbif name key using name_suggest and pick 1st suggestion if >1 or add blank row if no match, then get GBIF
```

```
taxonomy
# 1.1
LC.gbif.key = function (full_name) {
  gbif.key = name_backbone(name = full_name, rank = 'species',kingdom = 'Plantae', strict = TRUE, verbose =
FALSE) ### NOTE: try name_backbone instead, so we can make filter on kingdom = PLANTAE

  # add blank row when there is no value returned
  if(gbif.key$matchType=="NONE"){
    key = "NA"
    canonicalName = "NA"
    gbif.key = data.frame(key,canonicalName, stringsAsFactors = FALSE)
  }  else {
  # now reformat output of
    key = gbif.key$usageKey
    canonicalName = gbif.key$canonicalName
    gbif.key = data.frame(key, canonicalName,stringsAsFactors = FALSE)
  }
  # modify field headings to keep clean
  colnames(gbif.key)[which(names(gbif.key) == "key")] = "GBIF_SuggestedKey"
  colnames(gbif.key)[which(names(gbif.key) == "canonicalName")] = "GBIF_SuggestedName"
  gbif.key = gbif.key[, 1:2]
  gbif.key = data.frame(gbif.key, stringsAsFactors = FALSE)
  return(gbif.key)
}
# 1.2 - results.keys
LC.get.keys = function(full_name) {
  apply.gbif.key = lapply(full_name, LC.gbif.key)
  keys = do.call(rbind, apply.gbif.key)
  #keys.results = cbind(keys,LC.table[1],ID_list[2]) %>% as.data.frame()
  # update
  return(keys)
}
# 1.3 - get higher taxonomy for taxonomy.csv
LC.gbif.tax = function (result.table.keys) {
  if ((result.table.keys) == "NA") {
    # add new column to results and call it warning
    kin = ""
    phy = ""
    ord = ""
    fam = ""
    GBIF_SuggestedGen = ""
    GBIF_SuggestedSpe = ""
    GBIF_Suggestedauth = ""
    GBIF_SuggestedNameStatus = ""
    GBIF_SuggestedKey = ""
    GBIF_AcceptedKey = ""
    Warning = "No name match in GBIF"
    taxlist = data.frame(
      GBIF_SuggestedKey,
      kin,
      phy,
      ord,
      fam,
      GBIF_SuggestedGen,
```

```
    GBIF_SuggestedSpe,
    GBIF_Suggestedauth,
    GBIF_SuggestedNameStatus,
    GBIF_AcceptedKey,
    Warning
   )
  } else {
   # filter out NA
   # filter on key only - suggested key
   gbif_nam_search = name_usage(result.table.keys, rank = 'family')
   kin = gbif_nam_search$data$kingdom
   phy = gbif_nam_search$data$phylum
   ord = gbif_nam_search$data$order
   fam = gbif_nam_search$data$family
   GBIF_SuggestedGen = gbif_nam_search$data$genus
   GBIF_SuggestedSpe = gbif_nam_search$data$species
   GBIF_Suggestedauth = gbif_nam_search$data$authorship
   GBIF_SuggestedNameStatus = gbif_nam_search$data$taxonomicStatus
   GBIF_SuggestedKey = as.character(gbif_nam_search$data$key)
   GBIF_AcceptedKey = as.character(gbif_nam_search$data$speciesKey)
   Warning = ""
   taxlist = data.frame(
    GBIF_SuggestedKey,
    kin,
    phy,
    ord,
    fam,
    GBIF_SuggestedGen,
    GBIF_SuggestedSpe,
    GBIF_Suggestedauth,
    GBIF_SuggestedNameStatus,
    GBIF_AcceptedKey,
    Warning
   ) #gbifkey
  }
  search.df = c(
   "PROPARTE_SYNONYM",
   "DOUBTFUL",
   "HETEROTYPIC_SYNONYM",
   "HOMOTYPIC_SYNONYM",
   "MISAPPLIED",
   "SYNONYM"
  )
  taxlist$Warning[taxlist$GBIF_SuggestedNameStatus %in% search.df] = "GBIF matched name not treated as
accepted"
  return(taxlist = as.data.frame(taxlist))
}
# 1.4 - combine functions into one query to get keys and tax
LC.get.keys.tax = function(full_name, ID_list) {
  result.keys = LC.get.keys(full_name) # 1 - lapply on gbif key and merge back to get results table which will be
appended to later
  result.table.keys = cbind(ID_list, full_name, result.keys)
  result.tax = lapply(result.table.keys[, 3], LC.gbif.tax)
  result.tax = do.call(bind_rows, result.tax)
```

```
  result.table.tax = cbind(ID_list, full_name, result.tax)
  colnames(result.table.tax)[which(names(result.table.tax) == "ID_list")] = "POWO_ID"
  return(result.table.tax)
}

# 2 - get tdwg areas # and convert to country csv
# 2.0
LC.tdwg = function(ID) {
  #ID = "665137-1"
  full_url =  paste("http://plantsoftheworldonline.org/api/1/taxon/urn:lsid:ipni.org:names:", ID, sep = "")
  raw.data <- readLines(full_url, warn = "F", encoding = "UTF-8")
  rd <- fromJSON(raw.data)
  if (length(rd$distributions) == 0) {
    nat_dis = data.frame(
      tdwgCode = "NA",
      featureId = "NA",
      tdwgLevel = "NA",
      establishment = "NA",
      LEVEL3_NAM = "NA",
      POWO_ID = ID,
      TDWG_Name = "NA",
      ID = "",
      countryoccurrencename = "NA",
      countryoccurrencelookup = "NA",
      area = "NA",
      forest_loss = "NA",
      hfoot = "NA",
      w_forest_loss = "NA",
      w_hfoot = "NA")
  }

  else{
    nat_dis = rd$distributions
    nat_dis["POWO_ID"] = ID
    colnames(nat_dis)[which(names(nat_dis) == "name")] = "LEVEL3_NAM"
    colnames(TDWG_to_IUCN_version1_UTF_8)[which(names(TDWG_to_IUCN_version1_UTF_8) ==
"Level.3.code")] =
      "tdwgCode"
    nat_dis = merge(nat_dis, TDWG_to_IUCN_version1_UTF_8, by = "tdwgCode")

    #replace Panamá with Panama
    nat_dis$LEVEL3_NAM = gsub("Panamá", "Panama", nat_dis$LEVEL3_NAM)
    return(nat_dis)
  }
}

LC.countries = function(unique.sp, result.tdwg) {
  #unique.sp = unique.sp[1]
  result.tdwg.reduced = subset(result.tdwg, subset = result.tdwg$POWO_ID ==
                                 unique.sp)
  colnames(TDWG_to_IUCN_version1_UTF_8)[which(names(TDWG_to_IUCN_version1_UTF_8) ==
"Level.3.code")] =
    "tdwgCode"
  country.merge = merge(result.tdwg.reduced, TDWG_to_IUCN_version1_UTF_8, by = "tdwgCode")
```

```
  country.merge = distinct(country.merge, countryoccurrencename, .keep_all = TRUE)
  powoid = country.merge$POWO_ID
  countries = data.frame(
    internal_taxon_id = powoid,
    CountryOccurrence.CountryOccurrenceSubfield.CountryOccurrenceLookup =
country.merge$countryoccurrencelookup,
    CountryOccurrence.CountryOccurrenceSubfield.CountryOccurrenceName = country.merge$countryoccurrencename,
    CountryOccurrence.CountryOccurrenceSubfield.presence = 'Extant',
    CountryOccurrence.CountryOccurrenceSubfield.origin = country.merge$establishment,
    CountryOccurrence.CountryOccurrenceSubfield.seasonaility = 'Resident'
  )
  return(countries)
}

# 2.1 - collect errors i.e. no TDWG data and update results table
LC.tdwg.apply = function(ID_list) {
  apply.countries = lapply(ID_list, LC.tdwg)
  tdwg = do.call(rbind, apply.countries)
  return(tdwg) # add tdwg, to outputs
}
# 2.2
LC.tdwg.errors = function(result.tdwg) {
  errors = subset(result.tdwg, (LEVEL3_NAM == "NA"))
  errors = errors[, 6, drop = FALSE]
  return(errors)
}

# 3 - use GBIF keys to get points

# 3.0 - count occurrences from GBIF key
LC_count_occs = function(gbifkey){
  count = occ_count(taxonKey=gbifkey, georeferenced=TRUE)
  #count = cbind(count,gbifkey)
  return(count)
}
# this function get the data from gbif
download_bigkeys = function(dkeys){
  dkeys = dkeys[1]
  occ_download_get(dkeys, overwrite = TRUE) %>% occ_download_import()
}
# clean points
big_clean = function(big_points){


  if (!"recordNumber" %in% colnames(big_points)) {
    big_points$recordNumber = NA
    as.character(big_points$recordNumber)
  }

  if (!"decimalLongitude" %in% colnames(big_points)) {
    big_points$decimalLongitude = NA
    as.character(big_points$decimalLongitude)
  }
```

```
if (!"decimalLatitude" %in% colnames(big_points)) {
  big_points$decimalLatitude = NA
  as.character(big_points$decimalLatitude)
}

if (!"year" %in% colnames(big_points)) {
  big_points$year = NA
  as.character(big_points$year)
}

if (!"datasetKey" %in% colnames(big_points)) {
  big_points$datasetKey = NA
}

if (!"basisOfRecord" %in% colnames(big_points)) {
  big_points$basisOfRecord = NA
}

if (!"catalogNumber" %in% colnames(big_points)) {
  big_points$catalogNumber = NA
}

if (!"recordedBy" %in% colnames(big_points)) {
  big_points$recordedBy = NA
}

if (!"issues" %in% colnames(big_points)) {
  big_points$issues = NA
}

if (!"institutionCode" %in% colnames(big_points)) {
  big_points$institutionCode = NA
}

if (!"country" %in% colnames(big_points)) {
  big_points$country = NA
}

if (!"familyKey" %in% colnames(big_points)) {
  big_points$familyKey = NA
  as.character(big_points$familyKey)
}

if (!"scientificName" %in% colnames(big_points)) {
  big_points$scientificName = NA
}


big_points_clean = subset(big_points,    select = c(
  'basisOfRecord',
  'datasetKey',
  'taxonKey',
  'familyKey',
  'scientificName',
```

```
    'decimalLongitude',
    'decimalLatitude',
    'year',
    'issues',
    'country',
    'recordNumber',
    'catalogNumber',
    'recordedBy',
    'institutionCode'
  ))
}
# this function kicks off the downloads for all of the big keys
# as we can only have three at a time, it waits 10 mins (a little less than max) and then starts on the next in the list
get_bigkeys = function(big_gbifkeys){
  #taxonKey = as.data.frame(big_gbifkeys$gbifkey)
  download_text = paste0("occ_download(","'taxonKey = ",big_gbifkeys,"','hasGeospatialIssue = 
FALSE','hasCoordinate = TRUE')")
  eval(parse(text = download_text))
  Sys.sleep(900) # change to 10 minutes i.e. 600
}

gbif_queue <- function(...) {
  reqs <- lazyeval::lazy_dots(...)
  results <- list()
  groups <- split(reqs, ceiling(seq_along(reqs)/3))

  for (i in seq_along(groups)) {
    cat("running group of three: ", i)
    res <- lapply(groups[[i]], function(w) {
      tmp <- tryCatch(lazyeval::lazy_eval(w), error = function(e) e)
      if (inherits(tmp, "error")) {
        "http request error"
      } else {
        tmp
      }
    })

    # filter out errors
    res_noerrors <- Filter(function(x) inherits(x, "occ_download"), res)
    still_running <- TRUE
    while (still_running) {
      metas <- lapply(res_noerrors, occ_download_meta)
      status <- vapply(metas, "[[", "", "status", USE.NAMES = FALSE)
      still_running <- !all(tolower(status) %in% c('succeeded', 'killed'))
      Sys.sleep(2)
    }
    results[[i]] <- res
  }

  results <- unlist(results, recursive = FALSE)

  return(results)
}
```

```
# 3.1 - get points from gbif using clean keys
LC.gbif.points = function(gbifkey, result.tdwg) {
  #gbifkey = result.table
  #gbifkey = result.table[,3]

  if (gbifkey == "") {
    basisOfRecord = as.character("NA")
    datasetKey = as.character("NA")
    taxonKey = as.character("NA")
    familyKey = as.integer("-999")
    scientificName = as.character("NA")
    decimalLongitude = as.numeric("-999")
    decimalLatitude = as.numeric("-999")
    year = as.integer("-999")
    issues = as.character("NA")
    country = as.character("NA")
    recordNumber = as.character("NA")
    catalogNumber = as.character("NA")
    recordedBy = as.character("NA")
    institutionCode = as.character("NA")

    res = data.frame(
      datasetKey,
      basisOfRecord,
      taxonKey,
      familyKey,
      scientificName,
      decimalLongitude,
      decimalLatitude,
      year,
      issues,
      country,
      recordNumber,
      catalogNumber,
      recordedBy,
      institutionCode,
      stringsAsFactors = FALSE
    )
  } else    {
    #res = occ_search(taxonKey = gbifkey, hasGeospatialIssue = FALSE , hasCoordinate = TRUE, fields=c('taxonKey',
'familyKey', 'scientificName','basisOfRecord','issues', 'decimalLatitude','hasCoordinate',
'decimalLongitude','year','recordNumber','recordedBy','catalogNumber', 'datasetKey',
'country','institutionCode'),limit=200000)

    res = occ_data(
      taxonKey = gbifkey,
      hasGeospatialIssue = FALSE,
      hasCoordinate = TRUE,
      #geometry = 'POLYGON((-105.253164768219 25.917780721001716,-79.237539768219 25.917780721001716,-
79.237539768219 5.746349439479163,-105.253164768219 5.746349439479163,-105.253164768219
25.917780721001716))',
      limit = 200000
    )
```

```
res$data$taxonKey = gbifkey
res = res$data
res = as.data.frame(res)


if (!"recordNumber" %in% colnames(res)) {
  res$recordNumber = NA
  as.character(res$recordNumber)
}

if (!"decimalLongitude" %in% colnames(res)) {
  res$decimalLongitude = NA
  as.character(res$decimalLongitude)
}

if (!"decimalLatitude" %in% colnames(res)) {
  res$decimalLatitude = NA
  as.character(res$decimalLatitude)
}

if (!"year" %in% colnames(res)) {
  res$year = NA
  as.character(res$year)
}

if (!"datasetKey" %in% colnames(res)) {
  res$datasetKey = NA
}

if (!"basisOfRecord" %in% colnames(res)) {
  res$basisOfRecord = NA
}

if (!"catalogNumber" %in% colnames(res)) {
  res$catalogNumber = NA
}

if (!"recordedBy" %in% colnames(res)) {
  res$recordedBy = NA
}

if (!"issues" %in% colnames(res)) {
  res$issues = NA
}

if (!"institutionCode" %in% colnames(res)) {
  res$institutionCode = NA
}

if (!"country" %in% colnames(res)) {
  res$country = NA
}

if (!"familyKey" %in% colnames(res)) {
```

```
      res$familyKey = NA
      as.character(res$familyKey)
    }

    if (!"scientificName" %in% colnames(res)) {
      res$scientificName = NA
    }
  }

  res = subset(
    res,
    select = c(
      'basisOfRecord',
      'datasetKey',
      'taxonKey',
      'familyKey',
      'scientificName',
      'decimalLongitude',
      'decimalLatitude',
      'year',
      'issues',
      'country',
      'recordNumber',
      'catalogNumber',
      'recordedBy',
      'institutionCode'
    )
  )
  return(res)
}
# 3.2 - clean the points so they are ready for TDWG raster
clean.points = function(points) {
  points.clean = points[!is.na(points$decimalLongitude),]
  if (nrow(points.clean) < 1) {

  }  else {
    long = points.clean$decimalLongitude
    lat = points.clean$decimalLatitude
    coords = cbind(long, lat)
    coords <- data.matrix(coords)
    sp = SpatialPoints(coords)
    return(sp)
  }
}
# 3.3 - make copy of clean points as data.frame to merge back to later
clean.points.df = function(points) {
  points.clean.df = points[!is.na(points$decimalLongitude),]
  if (nrow(points) < 1) {

  }  else {
    return(points.clean.df)
  }
} # check if this needed
```

```
# 4 - get TDWG values and clip points so that only native are being used - check native
# 4.1  extract tdwg raster values
LC.extract.tdwg = function(points.clean.df, raster.tdwg) {
  if (nrow(points.clean.df) < 1) {

  }  else {
    decimalLongitude = points.clean.df$decimalLongitude
    decimalLatitude = points.clean.df$decimalLatitude
    coords = cbind(decimalLongitude, decimalLatitude)
    coords <- data.matrix(coords)
    coords = unique(coords)
    sp = SpatialPoints(coords)



    # extract values from raster for each point lat long
    extract.out = raster::extract(raster.tdwg, sp, df = TRUE)
    extract.out = cbind(extract.out, coords)

    # change column names for raster out and points so that you can do merge - also subset to get rid of NA
    colnames(extract.out)[which(names(extract.out) == "tdwg3")] = "VALUE"
    merge = merge(extract.out, tdwg_raster, by = "VALUE", all.x = TRUE)
    tdwg.merge.out = subset(merge, LEVEL3_NAM != "NA") # this gets rid of TDWG areas that had no points in
    #tdwg.merge.out = tdwg.merge.out[order(tdwg.merge.out$ID),]
    # final bind back to points
    point.clean.bind = merge(
      points.clean.df,
      tdwg.merge.out[, c(3, 4, 5)],
      by = c("decimalLongitude", "decimalLatitude"),
      all = TRUE
    )
    return(point.clean.bind)
  }
}
# 4.2 merge tdwg.extract with result.tdwg to only get native points in native distributions
native = function(tdwg.extract, powo.list, result.tdwg) {
  if (is.null(tdwg.extract)) {

  }  else {
    l = powo.list[1,]
    powo.max = nrow(powo.list)
    powo.list = powo.list[2:powo.max,]

    points.sub = subset(tdwg.extract, subset = (tdwg.extract["POWO_ID"] ==
                                                  l))
    #points.sub = tdwg.extract[ which==powo.list,]
    tdwg.sub = subset(result.tdwg, subset = (result.tdwg["POWO_ID"] == l))
    vars = "LEVEL3_NAM"
    tdwg.sub = tdwg.sub[vars]
    NativeWarning = ""
    first.merge = merge(points.sub, tdwg.sub, by = "Level.3.code")
    first.merge = cbind(first.merge, NativeWarning = NativeWarning)

    if (nrow(first.merge) < 1) {
      #add blank row with empty results
```

```
    NativeWarning = "No GBIF points in native range"
    first.merge = cbind(tdwg.extract, NativeWarning = NativeWarning)
  }

  for (l in powo.list) {
    #l = "77110432-1"
    points.sub = subset(tdwg.extract, subset = (tdwg.extract["POWO_ID"] ==
                                                 l))
    #points.sub = tdwg.extract[ which==powo.list,]
    tdwg.sub = subset(result.tdwg, subset = (result.tdwg["POWO_ID"] == l))
    vars = "LEVEL3_NAM"
    tdwg.sub = tdwg.sub[vars]
    list.merge = merge(points.sub, tdwg.sub, by = "LEVEL3_NAM")
    NativeWarning = ""
    list.merge = cbind(list.merge, NativeWarning = NativeWarning)
    list.merge = rbind(list.merge, first.merge)
    return(list.merge)
  }
 }
}

# 4.3 query ecoregions to get ecoregion count
LC.extract.eco = function(unique.sp, native_only, raster.eco)
 if (nrow(native_only) < 1) {

 }  else {
  unique.sp = unique.sp[1]
  species.points = subset(native_only, subset = native_only$POWO_ID ==
                          unique.sp)
  decimalLongitude =  species.points$decimalLongitude
  decimalLatitude =  species.points$decimalLatitude
  coords = cbind(decimalLongitude, decimalLatitude)
  coords <- data.matrix(coords)
  coords = unique(coords)
  sp = SpatialPoints(coords)

  # extract values from raster for each point lat long
  extract.out = raster::extract(raster.eco, sp, df = TRUE)
  extract.out = cbind(extract.out, coords)

  ecocount = length(unique(extract.out$eco2017))
  eco.res = data.frame(EcoregionCount = ecocount, POWO_ID = unique.sp)
  return(eco.res)
 }

# 5 calculate EOO and AOO
LC.eoo.aoo = function(unique.sp, native_only) {
 #get the points and project
 sp = subset(native_only, subset = native_only$POWO_ID == unique.sp)
 sp.ddlong = sp$decimalLongitude
 sp.ddlat = sp$decimalLatitude
 mypointsll = data.frame(lat = sp.ddlat, long = sp.ddlong)
 centreofpoints <- trueCOGll(mypointsll)
 mypointsxy <- simProjWiz(mypointsll, centreofpoints)
```

```
  #EOO and AOO calculation
  EOOm2 <- EOOarea(mypointsxy)
  EOOkm2 <- EOOm2 / 1000000
  EOOkm2abs = abs(EOOkm2)
  rec_count = nrow(mypointsxy)
  cellsizem <- 10000
  AOOnocells <- AOOsimp (mypointsxy, cellsizem)

  # extra field to find if any recent collection
  coll.last10yrs =

    eoo.aoo.res = data.frame(
      EOO = EOOkm2abs,
      AOO = AOOnocells,
      RecordCount = rec_count,
      POWO_ID = unique.sp
    )

  #eoo.aoo.res = do.call(rbind, res)
  return(eoo.aoo.res)
}

#6 get IUCN point file
LC.point.file = function(unique.sp, native_only, result.table) {
  #unique.sp = unique.sp[1]
  #native_only = native_only[,1]
  pointsLC = subset(native_only, subset = native_only$POWO_ID == unique.sp)
  GetYrCompiled = substring(Sys.Date(), 1, 4)
  GetSpatialRef = "WGS84"
  gbif_dataset = 'http://www.gbif.org/dataset/'
  res.tab = subset(result.table, subset = result.table$POWO_ID == unique.sp)
  Binomial = res.tab$GBIF_SuggestedSpe
  respath = paste0(path, Binomial, ".csv")
  iucn_point_file = data.frame(
    Binomial = Binomial,
    Presence = '1',
    Origin = '1',
    Seasonal = '1',
    Compiler = pointcompiler,
    Year = GetYrCompiled,
    Dec_Lat = pointsLC$decimalLatitude,
    Dec_Long = pointsLC$decimalLongitude,
    SpatialRef = GetSpatialRef,
    Event_Year = pointsLC$year,
    Citation = pointcitation,
    Source = paste0(gbif_dataset, pointsLC$datasetKey),
    BasisOfRec = pointsLC$basisOfRecord,
    CatalogNo = pointsLC$catalogNumber,
    recordedBy = pointsLC$recordedBy,
    recordNumber = pointsLC$recordNumber
  )
  FinalResult = write.table(
    iucn_point_file,
```

```
    respath,
    row.names = FALSE,
    na = "",
    sep = ","
  )
}

#7 generate the SIS files
LC.credits = function(LC.results) {
  #credits = data.frame(LC.results)[1,]
  powoid = LC.results[["POWO_ID"]]
  credits = data.frame(
    internal_taxon_id = powoid,
    credit_type = credittype,
    firstName = Firstname,
    lastName = Lastname,
    initials = Initials,
    Order = "1",
    email = Email,
    affiliation = Affiliation,
    user_id = "1"
  )
  return(credits)
}
LC.taxonomy = function(IUCN_taxonomy, LC.results) {
  #LC.results = result.table

  # filter to get those where GBIF and IUCN families matched and use IUCN higher taxonomy
  # leave those that don't match as blank and let user decide
  tax = full_join(IUCN_taxonomy, LC.results, by = "fam", copy = FALSE)
  tax_matched = subset(
    tax,
    select = c(
      Kingdom,
      Phylum,
      Class ,
      Order,
      fam,
      IUCN_fam,
      POWO_ID,
      GBIF_SuggestedGen,
      GBIF_SuggestedSpe,
      GBIF_Suggestedauth
    )
  )
  tax_good = tax_matched[complete.cases(tax_matched),]
  tax_unmatched = subset(tax_matched, (!is.na(tax_matched[, 7])))
  tax_unmatched = subset(tax_unmatched, (is.na(tax_unmatched[, 6])))
  tax_comb = rbind(tax_good, tax_unmatched)
  tax_comb$internal_taxon_id = tax_comb$POWO_ID
  tax_comb$kingdom = tax_comb$Kingdom
  tax_comb$phylum = tax_comb$Phylum
  tax_comb$classname = tax_comb$Class
  tax_comb$ordername = tax_comb$Order
```

```
  tax_comb$family = tax_comb$IUCN_fam
  tax_comb$genus = tax_comb$GBIF_SuggestedGen
  tax_comb$species = tax_comb$GBIF_SuggestedSpe
  tax_comb$taxonomicAuthority = tax_comb$GBIF_Suggestedauth
  tax_comb = tax_comb %>% separate(species, into = c("gen", "species"), sep = " ") %>% as.data.frame()
  tax_comb = subset(tax_comb, select = -c(1:10, 18))
  return(tax_comb)
}
LC.biorealms = function(TDWG_realms, result.tdwg) {
  #add realms using TDWG_realms table - first change column name to get match with result.tdwg
  colnames(TDWG_realms) [which(names(TDWG_realms) == "LEVEL3_COD")] = "tdwgCode"
  #merge result.tdwg and TDWG_realms so we have realms linked to POWO ID
  realms = merge(TDWG_realms, result.tdwg, by.x = "tdwgCode", by.y = "tdwgCode")
  # summarise and collapse to get single column with all unique realms - nice!
  biorealm_summary = realms %>% dplyr::group_by(POWO_ID) %>% dplyr::summarise(newREALM =
paste(unique(REALM), collapse =
                                                   ","))
  make_biorealms = data.frame(POWO_ID = biorealm_summary$POWO_ID,
                              biogeographicrealm.realm = (gsub("," , "\\|", biorealm_summary$newREALM)))
  return(make_biorealms)

}
LC.assessments = function(LC.results, biorealms) {
  #result.table = as.data.frame(result.table)[1,]
  #assessLC = subset(result.table, subset= result.table$POWO_ID==unique.sp)
  #join biorealms to assessments and update
  LC.results = merge(LC.results, biorealms, by = "POWO_ID")
  biogeographicrealm.realm = LC.results[["biogeographicrealm.realm"]]
  Rating = 'LC'   #Rating
  Rationale = paste(
    LC.results[["full_name"]],
    " has a wide distribution range across ",
    LC.results$TDWGCount,
    " countries and is known from ",
    LC.results$RecordCount,
    " occurrence records. Due to the wide range and lack of any major threats to this species at present the rating of
Least Concern is the most appropriate category.",
    sep = "",
    collapse = NULL
  )
  PopTrend = 'Stable'
  System = 'Terrestrial'
  mapstatus = 'Incomplete'
  sysdate = Sys.Date()
  day = substr(sysdate, 9, 10)
  month = substr(sysdate, 6, 7)
  year = substr(sysdate, 1, 4)
  date = paste0(day, "/", month, "/", year)
  version = "3.1"
  language = "English"
  internal_taxon_id = LC.results[["POWO_ID"]]
  range_nar = ""
  pop_nar = ""
  hab_nar = ""
```

```
  threat_nar = ""
  redlistcriteria.ismanual = "TRUE"

  assessments = data.frame(
    internal_taxon_id = internal_taxon_id,
    RedListRationale.value = Rationale,
    mapstatus.status = mapstatus,
    RedListAssessmentDate.value = date,
    RedListCriteria.critVersion = version,
    RedListCriteria.manualCategory = Rating,
    PopulationTrend.value = PopTrend,
    System.value = System,
    language.value = language,
    rangedocumentation.narrative = range_nar,
    populationdocumentation.narrative = pop_nar,
    habitatdocumentation.narrative = hab_nar,
    threatsdocumentation.value = threat_nar,
    redlistcriteria.ismanual = redlistcriteria.ismanual,
    biogeographicrealm.realm = biogeographicrealm.realm
  )

  return(assessments)
}
LC.habitats = function(LC.results) {
  powoid = LC.results[["POWO_ID"]]
  habitats = data.frame(
    internal_taxon_id = powoid,
    GeneralHabitats.GeneralHabitatsSubfield.GeneralHabitatsLookup = "18",
    GeneralHabitats.GeneralHabitatsSubfield.GeneralHabitatsName = "Unknown",
    GeneralHabitats.GeneralHabitatsSubfield.majorImportance = "",
    GeneralHabitats.GeneralHabitatsSubfield.season = "",
    GeneralHabitats.GeneralHabitatsSubfield.suitability = "Unknown"
  )
  return(habitats)
}
LC.plantspecific = function(LC.results) {
  powoid = LC.results[["POWO_ID"]]
  plantspecific = data.frame(
    internal_taxon_id = powoid,
    PlantGrowthForms.PlantGrowthFormsSubfield.PlantGrowthFormsLookup = "",
    PlantGrowthForms.PlantGrowthFormsSubfield.PlantGrowthFormsName = ""
  )
  return(plantspecific)
}
LC.allfields = function(LC.results) {
  powoid = LC.results[["POWO_ID"]]
  trendderiv = "Suspected"
  eoores = LC.results[["EOO"]]
  eoojust = "Minimum Convex Polygon (MCP) based on attached point file."
  nothreats.nothreats = "TRUE"
  threatsunknown.value = "FALSE"
  allfields = data.frame(
    internal_taxon_id = powoid,
    CurrentTrendDataDerivation.value = trendderiv,
```

```
    EOO.range = eoores,
    EOO.justification = eoojust,
    nothreats.nothreats = nothreats.nothreats,
    threatsunknown.value = threatsunknown.value
  )
  return(allfields)
}
LC.countries = function(unique.sp, result.tdwg) {
  #unique.sp = unique.sp[1]
  result.tdwg.reduced = subset(result.tdwg, subset = result.tdwg$POWO_ID ==
                               unique.sp)
  colnames(TDWG_to_IUCN_version1_UTF_8)[which(names(TDWG_to_IUCN_version1_UTF_8) ==
"Level.3.code")] =
    "tdwgCode"
  #country.merge = merge(result.tdwg.reduced,TDWG_to_IUCN_version1_UTF_8, by = "tdwgCode")
  country.merge = distinct(result.tdwg.reduced, countryoccurrencename, .keep_all = TRUE)
  powoid = country.merge$POWO_ID
  countries = data.frame(
    internal_taxon_id = powoid,
    CountryOccurrence.CountryOccurrenceSubfield.CountryOccurrenceLookup =
country.merge$countryoccurrencelookup,
    CountryOccurrence.CountryOccurrenceSubfield.CountryOccurrenceName = country.merge$countryoccurrencename,
    CountryOccurrence.CountryOccurrenceSubfield.presence = 'Extant',
    CountryOccurrence.CountryOccurrenceSubfield.origin =
      country.merge$establishment,
    CountryOccurrence.CountryOccurrenceSubfield.seasonaility = 'Resident'
  )
  return(countries)
}
LC.references = function(LC.results){
  #powoid = trees_7079[["ID"]]
  #powoid = powoid[1:10]
  powoid = LC.results[["POWO_ID"]]

  type = c("electronic source","electronic source","electronic source" )
  author = c("Board of Trustees, RBG Kew","Moat, J.", "Chamberlain, S")
  year = c("2018","2017", "2017")
  title = c("Plants of the World Online Portal", "rCAT: Conservation Assessment Tools. R package version
0.1.5.","rgbif: Interface to the Global 'Biodiversity' Information Facility API. R package version
          0.9.9.")
  place_published = c("Richmond, UK", "", "")
  url = c("http://powo.science.kew.org/","https://CRAN.R-project.org/package=rCAT", "https://CRAN.R-
project.org/package=rgbif")
  reference_type = c("Assessment","Assessment", "Assessment")
  references = data.frame(type, author, year, title, place_published, url, reference_type)
  references$internal_taxon_id = powoid[1]

  # make loop to create table with refs below and add powoid to each table, then bind together
  list = powoid[-1]

  for (l in list){
    type = c("electronic source","electronic source","electronic source" )
    author = c("Board of Trustees, RBG Kew","Moat, J.", "Chamberlain, S")
    year = c("2018","2017", "2017")
```

```
    title = c("Plants of the World Online Portal",
              "rCAT: Conservation Assessment Tools. R package version 0.1.5.",
              "rgbif: Interface to the Global 'Biodiversity' Information Facility API. R package version
              0.9.9.")
    place_published = c("Richmond, UK", "", "")
    url = c("http://powo.science.kew.org/","https://CRAN.R-project.org/package=rCAT", "https://CRAN.R-
project.org/package=rgbif")
    reference_type = c("Assessment","Assessment", "Assessment")
    all.references = data.frame(type, author, year, title, place_published, url, reference_type)
    all.references$internal_taxon_id = l
    references = rbind(references,all.references)
  }

  return(references)

}
LC.SIS.all = function(LC.results, unique.sp,result.tdwg,IUCN_taxonomy,biorealms) {
  sis.credits = LC.credits(LC.results)
  creditspath = paste0(path, "credits", ".csv")
  save.SIScredits = write.table(
    sis.credits,
    creditspath,
    row.names = FALSE,
    na = "",
    sep = ","
  )

  sis.taxonomy = LC.taxonomy(LC.results, IUCN_taxonomy)
  taxonomypath = paste0(path, "taxonomy", ".csv")
  save.SIStaxonomy = write.table(
    sis.taxonomy,
    taxonomypath,
    row.names = FALSE,
    na = "",
    sep = ","
  )

  sis.assessments = LC.assessments(LC.results, biorealms)
  assessmentspath = paste0(path, "assessments", ".csv")
  save.SISassessments = write.table(
    sis.assessments,
    assessmentspath,
    row.names = FALSE,
    na = "",
    sep = ","
  )

  sis.habitats = LC.habitats(LC.results)
  habitatspath = paste0(path, "habitats", ".csv")
  save.SIShabitats = write.table(
    sis.habitats,
    habitatspath,
    row.names = FALSE,
    na = "",
```

```
    sep = ","
  )

  sis.plantspecific = LC.plantspecific(LC.results)
  plantspecificpath = paste0(path, "plantspecific", ".csv")
  save.SISplantspecific = write.table(
    sis.plantspecific,
    plantspecificpath,
    row.names = FALSE,
    na = "",
    sep = ","
  )

  sis.allfields = LC.allfields(LC.results)
  allfieldspath = paste0(path, "allfields", ".csv")
  save.SISallfields = write.table(
    sis.allfields,
    allfieldspath,
    row.names = FALSE,
    na = "",
    sep = ","
  )

  sis.countries = lapply(unique.sp, LC.countries, result.tdwg)
  sis.countries = do.call(rbind, sis.countries)
  countriespath = paste0(path, "countries", ".csv")
  save.SIScountries = write.table(
    sis.countries,
    countriespath,
    row.names = FALSE,
    na = "",
    sep = ","
  )

  sis.references = LC.references(LC.results)
  referencespath = paste0(path, "references", ".csv")
  save.SISreferences = write.table(sis.references,referencespath, row.names = FALSE,na = "",sep = ",")
}

#8 Add result status: LC or 'Possibly threatened' based on predefined thresholds
#This is where you add the LC thresholds and decide what is LC e.g. >5 ecoregions, EOO > 40,000 etc.

LC.results = function(result.table) {
  #result.table = as.data.frame(result.table)
  dplyr::mutate(
    result.table,
    TDWGResult = ifelse(TDWGCount >= 4 & !is.na(TDWGCount), "LC", "Possibly threatened"),
    EcoregionResult = ifelse(EcoregionCount >= 5 & !is.na(EcoregionCount), "LC", "Possibly threatened"),
    EOOResult = ifelse(EOO > 30000 & !is.na(EOO), "LC", "Possibly threatened"),
    AOOResult = ifelse(AOO > 30 & !is.na(AOO), "LC", "Possibly threatened"),
    RecordResult = ifelse(RecordCount > 40 & !is.na(RecordCount), "LC", "Possibly threatened")
  )
}
```

```
LC.results.errors = function(result.table.errors){
  #add the extra rows here
  result.table.errors$TDWGResult = ""
  result.table.errors$EcoregionResult = ""
  result.table.errors$EOOResult = ""
  result.table.errors$AOOResult = ""
  result.table.errors$RecordResult = ""
  return(result.table.errors)
}

#8.1 make empty columns to ensure rbind works for good error and good species frames << NOT WORKING
error.tab = function(key.errors) {
  key.errors$TDWGCount = ""
  key.errors$EcoregionCount = ""
  key.errors$EOO = ""
  key.errors$AOO = ""
  key.errors$RecordCount = ""
  result.table.1 = key.errors
  rm(result.table)
}

#8.2 something extra - LC.variables - only if we have native points
# now I have area of TDWG, forest loss, weighted forest loss, human footp and weighted human footp
# I need to get sum of area and forest loss, human footp per species range e.g. one or more TDWG regions
# I need to divide sum of forest loss/hfoot by sum of area
# these are then normalised by area for each species and should then update the final result table
LC.variables = function(result.tdwg.native, unique.sp) {
  #normalise tdwg variables by area (tdwg L3 regions are different sizes)

  # make sure relevant fields are numbers - it won't summarise on characters
  result.tdwg.native = transform(result.tdwg.native, tdwgLevel = as.integer(tdwgLevel),
                                 ID = as.integer(ID),
                                 area = as.numeric(area),
                                 forest_loss = as.integer(forest_loss),
                                 hfoot = as.numeric(hfoot),
                                 w_forest_loss = as.numeric(w_forest_loss),
                                 w_hfoot = as.numeric(w_hfoot)
  )

  extras = result.tdwg.native %>% dplyr::group_by(POWO_ID) %>% dplyr::summarise(
    sum_w_forest_loss = sum(w_forest_loss, na.rm = TRUE),
    sum_w_hfoot = sum(w_hfoot, na.rm = TRUE),
    sum_area = sum(area, na.rm = TRUE),
    norm_forest_loss = sum_w_forest_loss / sum_area,
    norm_hfoot = sum_w_hfoot /  sum_area)
  extras = subset(extras, select = c(POWO_ID, norm_forest_loss, norm_hfoot))
}

##############################################################################
#9 These lines bring it all together ####################################
##############################################################################

RedLeast = function(full_name,ID_list,path,LC.points = FALSE,SIS.files = FALSE, BigKeys) {
```

```
  # 1 - Run the full_name against GBIF query to see if you get a name match. Return warning value in table if no
match
  keys.tax = LC.get.keys.tax(full_name, ID_list)
  key.errors = subset(keys.tax, (nchar(keys.tax$Warning) > 3))
  key.matches = subset(keys.tax, (nchar(keys.tax$Warning) < 3))

  # Run ID (POWO IDs) against POWO api to get TDWG regions
  result.tdwg = LC.tdwg.apply(ID_list)
  # Find the errors where there is no TDWG info in POWO
  tdwg.errors = LC.tdwg.errors(result.tdwg)
  # Use update.errors function to add error value to warning column
  result.table = update.errors(keys.tax, tdwg.errors, error.text = "No TDWG distribution data")
  #check for empty TDWG results and make table to join to main results at the end
  error.species = subset(result.table, (nchar(result.table$Warning) > 3))
  good.species = subset(result.table, (nchar(result.table$Warning) < 3))
  # print to check progress

  if (nrow(error.species) >= 1) {
    error.species$TDWGCount = ""
    error.species$EcoregionCount = ""
    error.species$EOO = ""
    error.species$AOO = ""
    error.species$RecordCount = ""
    # add/remove next two lines below when you do/don't want to calcualte forest loss, hfoot etc.
    error.species$norm_forest_loss = ""
    error.species$norm_hfoot = ""
    result.table.errors = error.species
    rm(result.table)
  }

  # 2 - are there GBIF point errors i.e. no georeferneced occurrence points
  if (nrow(good.species) >= 1) {
    result.table = good.species
    gbifkey = result.table[, 3]

    # count occurrences for each 'good species' and combine with gbif key
    count_occs = lapply(gbifkey,LC_count_occs)
    count_occs_tibb = tibble(count_occs) %>% unlist()
    gbifkey_df = as.data.frame(gbifkey)
    all_count = cbind(count_occs_tibb,gbifkey_df)

    # Filter out the big keys
    small_gbifkeys = subset(all_count, count_occs <=200000) %>% as.data.frame() # change to whatever is the
threshold e.g. 200,000
    small_gbifkeys = small_gbifkeys[,2]
    big_keys = subset(all_count, count_occs >200000) %>% as.data.frame() # change to whatever is the threshold e.g.
200,000?
    big_keys = big_keys[,2]
    print(paste0(big_keys))

    # not get the points
    apply.points = lapply(small_gbifkeys, LC.gbif.points) #if GBIF keys exists....
    points = do.call(rbind.fill, apply.points)
```

```
    # add POWO_ID to points because POWO ID is the unique value. join points.with.tdwg to result.table.tdwg
    powo.ids = cbind(POWO_ID = result.table$POWO_ID, taxonKey = result.table$GBIF_SuggestedKey) %>%
as.data.frame()
    points.with.powoid = merge(points, powo.ids, by = "taxonKey")
    smr = ddply(points.with.powoid, "POWO_ID",summarise,n = length(decimalLatitude),n_na =
sum(is.na(decimalLatitude)), prop_missing = n_na / n)
    gbif.point.errors = subset(smr, prop_missing == 1)
    gbif.point.errors = gbif.point.errors[1]
    result.table = update.errors(result.table, gbif.point.errors, error.text = "No GBIF points")

    # another break point to filter out error species that have no points
    noPoints.species = subset(result.table, (nchar(result.table$Warning) > 3))
    withPoints.species = subset(result.table, (nchar(result.table$Warning) < 3))

    if (nrow(noPoints.species) >= 1) {
      noPoints.species$TDWGCount = ""
      noPoints.species$EcoregionCount = ""
      noPoints.species$EOO = ""
      noPoints.species$AOO = ""
      noPoints.species$RecordCount = ""
      # add/remove next two lines below when you do/don't want to calcualte forest loss, hfoot etc.
      noPoints.species$norm_forest_loss = ""
      noPoints.species$norm_hfoot = ""
      rm(result.table)
    }

    # check if noPoints has any rows - if not, do nothing
    if (nrow(noPoints.species) >=1) {

      # if noPoints has rows, then check if error table exists
      if (exists("result.table.errors")) {

        # if error table exists, then rbind noPoints
        result.table.errors = rbind(result.table.errors,noPoints.species)
      } else {

        # otherwise make error table from points
        result.table.errors = noPoints.species
      }
    }



    #3 - Check species points against species' native TDWG range

    if (nrow(withPoints.species) >= 1) {
      #now I only need clean points i.e. use merge on POWO ID to remove taxa with no points
      points.with.powoid = semi_join(points.with.powoid, withPoints.species, by = "POWO_ID", copy = FALSE)
      points.clean.df = clean.points.df(points.with.powoid)
      rm(points)
      rm(points.with.powoid)
      tdwg.extract = LC.extract.tdwg(points.clean.df, raster.tdwg)
      rm(points.clean.df)
      powo.list = unique(tdwg.extract[15]) %>% as.data.frame()
      result.tdwg.native = subset(result.tdwg, establishment == "Native")
```

```
    colnames(result.tdwg.native)[which(names(result.tdwg.native) == "TDWG_Name")] = "Native_NAM"
    #colnames(result.tdwg)[which(names(result.tdwg) == "LEVEL3_NAM")] = "Native_NAM"
    countTDWG = ddply(result.tdwg.native,"POWO_ID", summarise,TDWGCount = length(tdwgCode))
    result.table = merge(withPoints.species, countTDWG, by = "POWO_ID")

    #4 - run final metrics on clean point data from native range
    # find the native only point
    native_only = inner_join(tdwg.extract,result.tdwg.native[, c("POWO_ID", "Native_NAM")], by = c("POWO_ID" =
"POWO_ID", "LEVEL3_NAM" = "Native_NAM"))

    # now find the non-native points and compare with native points.
    tdwg.extract.unmatched = anti_join(tdwg.extract,result.tdwg.native, by = c("POWO_ID" = "POWO_ID",
"LEVEL3_NAM" = "Native_NAM"))

    #If prop. non-native is 1 then mark as error
    sum.tdwg.extract = ddply(tdwg.extract, "POWO_ID", summarise,n = length(decimalLatitude))
    sum.unmatched = ddply(tdwg.extract.unmatched, "POWO_ID", summarise, n_non_native =
length(decimalLatitude))
    sum.merged = merge(sum.tdwg.extract,sum.unmatched, all = TRUE)
    sum.merged$prop_non_native = (sum.merged$n_non_native / sum.merged$n)
    gbif.native.errors = subset(sum.merged, prop_non_native == 1)
    result.table = update.errors(result.table, gbif.native.errors[1], error.text = "No GBIF points in range")

    # get 'points out of range' errors and add them to result.table.errors, then leave clean list for final analysis
    PointsOutofRange.species = subset(result.table, (nchar(result.table$Warning) > 3))
    PointsInRange.species = subset(result.table, (nchar(result.table$Warning) < 3))

    # need to update result.table.errors here with points out of range
    if (nrow(PointsOutofRange.species) >= 1){

      PointsOutofRange.species$EcoregionCount = ""
      PointsOutofRange.species$EOO = ""
      PointsOutofRange.species$AOO = ""
      PointsOutofRange.species$RecordCount = ""
      # add/remove next two lines below when you do/don't want to calcualte forest loss, hfoot etc.
      PointsOutofRange.species$norm_forest_loss = ""
      PointsOutofRange.species$norm_hfoot = ""
      rm(result.table)
    }

    # check if PointsOutofRange.species has any rows - if not, do nothing
    if (nrow(PointsOutofRange.species) >=1) {

      # if noPoints has rows, then check if error table exists
      if (exists("result.table.errors")) {

        # if error table exists, then rbind noPoints
        result.table.errors = rbind(result.table.errors,PointsOutofRange.species)
      } else {

        # otherwise make error table from points
        result.table.errors = PointsOutofRange.species
      }
    }
```

```
# Get list of unique species by POWO_IDs and run ecoregions function to get count of ecoregions per species
if (nrow(PointsInRange.species) >= 1) {

  native.points = semi_join(native_only, PointsInRange.species, by = "POWO_ID", copy = FALSE)
  unique.sp = unique(native.points$POWO_ID)
  eco.res = lapply(unique.sp, LC.extract.eco, native.points, raster.eco)
  eco.res = do.call(rbind, eco.res)
  # Join the ecoregion count to the result table
  result.table = full_join(PointsInRange.species, eco.res, by = "POWO_ID", copy = FALSE)

  # Run the native only points against the EOO and AOO scripts using rCAT package
  eoo.aoo.res = lapply(unique.sp, LC.eoo.aoo, native_only)
  eoo.aoo.res = do.call(rbind, eoo.aoo.res)
  # Join the EOO and AOO results to the result table
  result.table = full_join(result.table, eoo.aoo.res, by = "POWO_ID", copy = FALSE)

  # Calcualte biorealms for each species
  biorealms = LC.biorealms(TDWG_realms, result.tdwg)

  # now add the extra variables - forest loss and hfoot
  normalise.vars = LC.variables(result.tdwg.native,unique.sp)
  unique.sp.vars = as.data.frame(unique.sp)
  colnames(unique.sp.vars)[which(names(unique.sp.vars) == "unique.sp")] = "POWO_ID"
  var.update = merge(unique.sp.vars,normalise.vars, by = "POWO_ID")
  result.table = full_join(result.table, var.update, by = "POWO_ID", copy = FALSE)



  #if user declares LC.points = TRUE then save the point csv's
  #note that it doesn't mean species is LC - it will save all those that have point data
  if (LC.points) {
    all_points = lapply(unique.sp, LC.point.file, native_only, result.table)
    all_points = do.call(rbind, all_points)
    #FinalResult = write.table(
    #  iucn_point_file,
    #  respath,
    #  row.names = FALSE,
    #  na = "",
    #  sep = ","
    #)
  }

  #if user declares SIS.files = TRUE then save the SIS csv's
  if (SIS.files) {
    #LC.SIS.all(result.table,unique.sp,result.tdwg,IUCN_taxonomy,biorealms)
    #sis.credits = LC.credits(result.table)
    #sis.taxonomy = LC.taxonomy(result.table, IUCN_taxonomy)
    #sis.assessments = LC.assessments(result.table, biorealms)
    #sis.countries = lapply(unique.sp, LC.countries, result.tdwg)
    #sis.countries = do.call(rbind, sis.countries)
    #sis.allfields = LC.allfields(result.table)
    #sis.plantspecific = LC.plantspecific(result.table)
    #sis.habitats = LC.habitats(result.table)
```

```
      #sis.references = LC.references(result.table)
      LC.SIS.all(result.table,unique.sp,result.tdwg,IUCN_taxonomy,biorealms)


     }


    }
  }
}

#now save the results file - checks for either error or good species only and saves
#Or - if both error and good species exist, rbind these and then save

# make below into a function e.g.save.results = function()
respath = paste0(path, "Results", ".csv")
if (!exists("result.table.errors")) {
  #result.table = LC.results(result.table)
  #save.results = write.table(result.table, respath,row.names = FALSE,na = "", sep = ",")
  result.table = result.table
} else if (!exists("result.table")) {
  #result.table.errors = LC.results(result.table.errors)
  #save.results = write.table(result.table.errors,respath,row.names = FALSE,na = "",sep = ",")
  result.table = result.table.errors
} else {
  #result.table = LC.results(result.table)
  #result.table.errors = LC.results.errors(result.table.errors)
  result.table = rbind(result.table, result.table.errors)
  #save.results = write.table(result.table,respath,row.names = FALSE,na = "",sep = ",")
}



#######
####### Make this into a function
#######

####### Need to filter on those in the results where there is missing data
####### add 'threat' column
####### update those with missing data as Insufficient Data for prediction - not DD, as this is IUCN Category

# apply the prediction model - function all this up?
# load first
RedLeastRFmodel = readRDS("C:/Users/sb42kg/OneDrive - The Royal Botanic Gardens,
Kew/02_Publications/spb/Machine learning - big data red list/05_R/03_Model_Predict/RedLeastRFmodel.rds")

import = randomForest::importance(RedLeastRFmodel$finalModel, scale = FALSE)
# need to check that there is data for all variables first
# create a separate results table to do the prediction on
result.predict = result.table
#save.results = write.table( result.predict,respath,row.names = FALSE,na = "",sep = ",")

# change family to factors so that it can be used in the model (as integers)
# load the input data where you have original family names and integers
```

```
  fam <- read_csv("C:/Users/sb42kg/OneDrive - The Royal Botanic Gardens, Kew/02_Publications/spb/Machine learning - big data red list/05_R/03_Model_Predict/fam_converted.csv")

  # map this to the results table - merge
  result.predict = merge(fam, result.predict, by = "fam", all.y = TRUE)

  # clean up table
  result.predict = result.predict[-1]
  colnames(result.predict)[which(names(result.predict) == "fam_int")] = "fam"
  result.predict$fam[which(is.na(result.predict$fam))] <- 9999

  # match data types to training set
  result.predict$fam = as.integer(result.predict$fam)
  result.predict$RecordCount = as.integer(result.predict$RecordCount)
  result.predict$TDWGCount = as.integer(result.predict$TDWGCount)
  result.predict$EcoregionCount = as.integer(result.predict$EcoregionCount)
  result.predict$EOO = as.numeric(result.predict$EOO)
  result.predict$AOO = as.integer(result.predict$AOO)
  result.predict$norm_forest_loss = as.numeric(result.predict$norm_forest_loss)
  result.predict$norm_hfoot = as.integer(result.predict$norm_hfoot)

  #str(result.predict)

  # there may still be some NAs here - so model won't run
  # take these out and update result.table with DD flag
  na_rows = result.predict[rowSums(is.na(result.predict))>0,]
  na_rows$threat_prediction = "Insufficient Data"

  # these are the good ones for the model
  result.predict = anti_join(result.predict,na_rows, "POWO_ID")

  # use model to predict data from result.table
  threat_prediction <- predict(object = RedLeastRFmodel,
                          newdata = result.predict,
                          type = "raw")

  threat_prediction = as.data.frame(threat_prediction)

  # join back to result table
  model_result.table = cbind(result.predict,threat_prediction)
  #save.results = write.table(   result.table,respath,row.names = FALSE,na = "",sep = ",")

  #reduce to just powo id and threat
  model_result.table = model_result.table[,c(2,21)]

  model_res_merge = merge(model_result.table, result.table, by = "POWO_ID", copy = FALSE)
  #model_na_res_merge =


  # add the na_rows back in to get full results - add value for threat column?
  combined = rbind(model_res_merge,na_rows)

  # change family back to name from integer?
```

```
  save.results = write.table(combined,respath,row.names = FALSE,na = "",sep = ",")

  #######
  ####### Make this into a function
  #######



####### add the if statement to trigger this
# for (i in (result.table$full_name)){
#     rmarkdown::render(input = 'C:/Users/sb42kg/OneDrive - The Royal Botanic Gardens,
Kew/02_Publications/spb/Machine learning - big data red
list/05_R/04_Output_Assessments/markdown_species_reports/r_markdown.Rmd',
#                   output_file = paste("report_",i,".html", sep=""),
#                   output_dir =  'C:/Users/sb42kg/OneDrive - The Royal Botanic Gardens,
Kew/02_Publications/spb/Machine learning - big data red
list/05_R/04_Output_Assessments/markdown_species_reports/')
# }
#
# Try cross talk https://www.rstudio.com/resources/videos/linking-html-widgets-with-crosstalk/

  print(paste0("Results written to disk"))
  time_now = Sys.time()
  print(time_now)


  }
```