

**Modelling the Climate Sensitivity of Proso Millet (*Panicum
miliaceum* L.) in Sri Lanka**

Ganwari Eranga Madushan Wimalasiri

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**School of Biosciences, Faculty of Science, The University of Nottingham
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ABSTRACT

Proso millet (*Panicum miliaceum* L.) is a minor cereal cultivated as a subsistence crop in Africa and Asia. It is an essential crop in rainfed farming systems of dry areas in Low Country Sri Lanka where rainfall is the limiting factor for crop production. The crop's shorter lifespan, low water requirement and considerable yield in unfavourable environments are important adaptive features. It shows promise for high nutrient content and yield under marginal environmental conditions and is suggested as a crop that might be less affected by climate change. Proso millet in Sri Lanka is cultivated from local accessions/landraces as there are no varieties bred for specific traits. There is ample evidence to suggest that Sri Lanka's climate has already changed, and its agricultural sector is vulnerable to climate shocks. Therefore, it is important that these minor millets should receive research attention, which is the reason for selection of the crop. This study was designed to analyse the current status of Proso millet cultivation in Low Country Dry Zone Sri Lanka and to model the sensitivity of yield to climate change in mid-21st century through crop-climate modelling.

The present situation of Proso millet cultivation in Sri Lanka was initially studied using a combination of past data, on-farm field survey, field observations and field sampling approaches. Biomass samples were collected at harvesting stage from farmers' fields. High spatial variability was observed among fields due to different land preparation techniques, quality of seeds, seed rates and plant densities. The yields reported by farmers (ranged from 0.470 to 1.956 t ha⁻¹) were found to be far below the potential yield expected by the Department of Agriculture Sri Lanka (4 t ha⁻¹).

Growing season rainfall characteristics and their relationship with crop husbandry strategies in growing area were analysed to study the link between Proso millet cultivation and agro-climatic characteristics in the growing area in Sri Lanka. The growing season (15th March–15th June) rainfall characteristics, onset, retreat and length of the season, and trends of dry spells in the growing area were analysed using daily rainfall data collected from 5 meteorological stations for the period of 1983–2015. It was found that Proso millet cropping patterns in the study area coincided with the distribution of rainfall and that farmers adjust crop management practices and crop selection to minimise climate associated damages to cultivation.

Agricultural Production Systems Simulator (APSIM), which has been tested under different growing conditions, genotypes and environments across the world, was selected to simulate Proso millet production in Sri Lanka. Five farmer selections (hereafter mentioned as accessions) named as L_1, L_11, L_12, L_14 and L_25 and that had been collected from farmers' fields in Low Country Dry Zone Sri Lanka were tested. The data gathered from two field experiments (2016 July–October: dry season and 2017 February–April: rainy season) conducted at Sabaragamuwa University (6.70°N, 80.79°E) were used for model calibration. Observed crop phenology, leaf area index, biomass and yield from calibration experiments correlated well with the simulated values in the calibrated model suggesting a good calibration. The model was validated using the yield data collected from farmers' fields grown under different sowing dates, plant densities, soil properties and crop management practices. Simulation of grain yield was satisfactory (Root Mean Square Error 279 kg ha⁻¹) when compared with farmers' data, therefore, the model was used to study the climate sensitivity and future yield projections of Proso millet in Sri Lanka.

The future (2040–2069) climate of the Proso millet growing region in Sri Lanka was studied using data from 20 general circulation models of Coupled Model Intercomparison Project (CMIP5) under two greenhouse gas emission scenarios (RCP4.5 and 8.5). These data suggest a clear increase in temperature and a possibility of a wetter future in the mid-21st century in the area. The sensitivity of the crop to changes in temperature and precipitation was studied systematically using the protocol of the Coordinated Climate-Crop Modelling Project (C3MP of AgMIP: [The Agricultural Model Intercomparison and Improvement Project](#)). Simulated yields tend to increase with increases in rainfall if temperature increases by less than 2 °C, but all other combinations of change result in decreases in yield. Future climate mean yields simulated by APSIM were lower than the simulated yields using the baseline (1980–2009) climate under both RCP4.5 (–7.3%) and RCP8.5 (–16.6%) scenarios for 2040–2069 period though these changes were not significantly ($p > 0.05$) different from the baseline yields. Since the yields of major crops like rice are expected to have lower yields under similar climate change scenarios, Proso millet, that is grown with low inputs, without irrigation and fertiliser (most fields), will be an alternative crop that has the potential to be cultivated in Low Country Dry Zone Sri Lanka for mid-21st century under a changing climate.

This is the first attempt to evaluate the climate sensitivity of Proso millet using crop-climate modelling approaches, therefore, this study can be used as a baseline study to assess the climate sensitivity of other underutilised crops. The results can be used in decision making regarding the expansion of Proso millet cultivation in the future.

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LIST OF SYMBOLS AND ABBREVIATIONS

°C	Celsius
μS	Micro siemens
ac	Acres
AEZ	Agroecological zone
APSIM	Agricultural Production Systems Simulator
AR5	IPCC Fifth Assessment Report
BD	Bulk density
C3MP	Coordinated Climate-Crop Modelling Project
CCAFS	Consultative Group for International Agricultural Research (CGIAR) Research Program on Climate Change, Agriculture and Food Security
cm	Centimetres
CMIP5	Coupled Model Intercomparison Project phase 5
CO ₂	Carbon dioxide
CRI	Climate Risk Index
CV	Coefficient of variation
d	Days
DAE	Days After Emergence
DAS	Days After Sowing
DL _{1a}	Low Country Dry Zone region 1a
DL _{1b}	Low Country Dry Zone region 1b
DOASL	Department of Agriculture Sri Lanka
DSSAT	Decision Support System for Agrotechnology Transfer
DZ	Dry Zone
EC	Electrical conductivity
FIM	First Inter Monsoon
g	Grams
GCM	General Circulation Models
GDD	Growing degree days
GHG	Greenhouse gas
ha	Hectare

HARTI	Hector Kobbekaduwa Agrarian Research and Training Institute
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
L ₁	Accession 1
L ₁₁	Accession 11
L ₁₂	Accession 12
L ₁₄	Accession 14
L ₂₅	Accession 25
LAI	Leaf area index
LCDZ	Low Country Dry Zone
LKR	Sri Lanka Rupees
LSF	leaf shape factor
m	Meter
M _i	Measured value
mL	Millilitres
mLAI	Maximum leaf area index
mm	Millimetres
N	Nitrogen
NASA	National Aeronautics and Space Administration
NEM	North East Monsoon
N–S	Nash and Sutcliffe model efficiency criteria
OFC	Other Field Crops
POWER	Prediction of Worldwide Energy Resource
ppm	Parts per million
r	Correlation coefficient
R ²	Coefficient of determination
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
SD	Standard deviation
S _i	Simulated value
SIM	Second Inter Monsoon
SOI	Southern Oscillation Index

SRES	Special Report on Emissions Scenarios
SWM	South West Monsoon
t	Tons
TT	Thermal time
USDA	United States Department of Agriculture
Wm ⁻²	Watts per square meter

Chapter 1

General Introduction

1.1 Introduction

The agricultural production in low latitudes of the earth is expected to decline as a result of climate change-induced rising temperatures, increased evaporation that lead to water stress and changes in rainfall pattern (Rosenzweig 2011). Since most of the developing countries belong to lower latitude regions, the impact of climate change is severe for them including Sri Lanka, compared to the developed countries in mid to high latitudes (Parry et al. 2004). The vulnerability of developing countries to the climate change is higher because they often lack the resources to invest in adaptation measures (Rosenzweig 2011), therefore food security is an increasing challenge in this part of the world (Wheeler and Braun 2013).

Various adaptation strategies can be used to avoid yield losses due to climate change (Challinor et al. 2014) and developing resilient agricultural systems is a low cost and effective strategy to overcome the increased risk of droughts and other climatic hazards in the Asian region (IPCC 2014). Since climate change has a negative impact on several major crops like rice, wheat and maize (Lobell and Field 2007), the popularization of underutilised crops is viewed as a key response to produce more food with nutritional aspects. The potential of underutilised crops has not yet been realised and harnessed, but most of the underutilised crops adapted to marginal environments and contribute to diversification and resilience of agroecosystems, so they have a potential for future agriculture to fight against climate change (Padulosi et al. 2011).

The vulnerability of the Dry Zone (annual rainfall less than 1750 mm) and parts of the Intermediate Zone (annual rainfall 1750–2500 mm) to drought is increasing in Sri Lanka. Therefore, cultivation of drought-tolerant underutilised crops such as Proso millet is an efficient strategy for crop production in dry (Seghatoleslami et al. 2008) and drought-prone areas. Proso millet (*Panicum miliaceum* L.) is a minor cereal but staple food in some parts of Africa and Asia that is also found in rainfed farming systems of Low Country Dry Zone Sri Lanka (Chapter 3) and is a crop with short growing period (60–70 days) and low water requirement (Baltensperger 2002; Léder 2004; Lyon et al. 2008; Habiyaemye et al. 2017). It was highlighted as a crop that is particularly useful in a climate where rainfall might be less reliable (Swaminaidu et al. 2015). Available literature suggests that Proso millet is a stress tolerant plant and gives reasonable yields where other crops like maize and paddy fail to grow or give poor yields (Liu et al. 2014; Nirmalakumari et al. 2008; Ravi et al. 2010).

Sri Lanka does not emit a considerable amount of greenhouse gases to contribute to global warming, but that does not mean the country is safe from the consequences of climate change (Yamane 2009; Zoysa and Inoue 2014). The country is vulnerable to climate change in terms of rainfall variability and an increase in climate extremes and warming (De Costa 2008; Eriyagama and Smakhtin 2010; Esham and Garforth 2013; Zoysa and Inoue 2014; Zubair et al. 2015) and its agricultural sector is negatively affected by climate shocks (Zubair 2002; Zubair 2005). A recent example was the severe drought which lasted nearly 9 months in the year 2017 due to failure of South West and North East monsoons that reduced production of paddy (by 46.1%), coconut (18.7%) and vegetables (12.6%) (Central bank Sri Lanka 2017). This is further triggered by the fact that the country has been ranked 2nd in the Climate Risk Index (CRI) 2019 by ‘Germanwatch’ that is based on the extent of climate related losses such

as storms, floods, heat waves to the economy (Eckstein et al. 2019). The General Circulation Model (GCM) based climate projections also predict a hotter future all over Sri Lanka while both increment and reduction of future rainfall in different parts of the country (Jayatillake and Droogers 2004; Eriyagama and Smakhtin 2010; Zubair et al. 2015; Pattanayak et al. 2017). The yields of key crops like rice and maize are expected to decline due to the increment of temperature in the tropical region (Lobell and Field 2007; Karunaratne et al. 2015; Karunaratne and Wheeler 2015), but the climate sensitivity of minor crops like Proso millet has received less research attention.

Therefore, it is of prime importance to study the future climate in Sri Lanka and its impact on different crops. This project was designed to study the present situation of Proso millet cultivation in growing regions of Sri Lanka and to predict the yield in the mid-21st century and evaluate the sensitivity of yield to rainfall and temperature variables. Proso millet is common in subsistence farming systems in Low Country Dry Zone Sri Lanka (Malkanthi 2016) and used in this research due to the favourable characteristics of the crop to the climate change (Section 2.2). Different research approaches such as field survey, field experiments, crop and climate modelling were used in this study to evaluate the climate sensitivity of Proso millet in the future.

The scientific literature is scarce on Proso millet cultivation in Sri Lanka. This research addressed the fact that less improved cultivars of these species exist and therefore farmer selected landraces with variable genetic characters were collected from areas where they are growing in low input farming systems in the Dry Zone of Sri Lanka.

Prediction of climate change and the assessment of its impact on crop yield are important to identify adaptation strategies (Jones et al. 2015). Crop simulation modelling allows studying the potential of crops and crop varieties in different

geographic locations under different climates because traditional agronomic experiments are time-consuming and expensive (Chisanga et al. 2017). In order to overcome the lack of research evidence and to make a rapid progress with this study, quantification of crop-climate interactions was implemented through the crop modelling approach. APSIM (Agricultural Production Systems Simulator-Keating et al. 2003) that has been tested under different growing conditions, genotypes and environments across the world (Keating et al. 2003; Holzworth et al. 2014) was used to simulate Proso millet yields under variable climatic regimes. APSIM has been widely used to study the impact of climate change on crop production, adaptation and mitigation strategies in different geographical locations of the world (Holzworth et al. 2014; Madegwa 2015). APSIM applications in Sri Lanka were mainly reported on field crops (Suriyagoda and Peiris 2013; Zubair et al. 2015; Fernando et al. 2015; Nissanka et al. 2015; Wallach et al. 2017), but it has never been used to model Proso millet in Sri Lanka or elsewhere. In this study, five Proso millet accessions were collected from farmers in the growing regions of the country. The APSIM millet model was calibrated for these five accessions using the data gathered from the first field experiment and then fine-tuned from the second experiment. Crop management, production (yield), and soil data were collected from smallholder farmers and used for the evaluation of the APSIM model.

Overall then, a knowledge gap exists for the Proso Millet grown in Sri Lanka by smallholders in mixed farming systems. Little is known about preferred geographic locations and agricultural practices, or about climate resilience, but such knowledge could provide the basis for the expansion of production under future climates. This study entitled “Modelling the climate sensitivity of Proso millet in Sri Lanka” is the first attempt to project Proso millet yield in the mid-21st century using crop modelling

approaches. The output of this project can be used as a baseline study to evaluate the climate sensitivity of other underutilised crops grown in complex multi-cropping systems in Sri Lanka and globally.

1.2. Aim and the objectives of the study

The overall aim of this study was to evaluate the current status of Proso millet (*Panicum miliaceum* L.) cultivation in Sri Lanka and to analyse the sensitivity of production to a future changing climate through crop-climate modelling. This aim is achieved through the following specific objectives:

1. To analyse the present situation of Proso millet cultivation in Sri Lanka.
2. To evaluate the climate characteristics of the growing area in Sri Lanka.
3. To calibrate and to validate APSIM crop model for Proso millet.
4. To use Coordinated Climate-Crop Modelling Project (C3MP) methodology to evaluate crop yield sensitivity to climate variability using the calibrated APSIM model.
5. To study the future climate of Proso millet growing area and make projections for yield under future climate scenarios in the mid-21st century (2040–2069).

The schematic diagram (Figure 1.1) illustrates the link between specific objectives (S.O.) of the overall study.

1.3. Thesis outline

The outline of the thesis is as follows, with each chapter mapping on to S.O.s mentioned above.

- **Chapter 2** is a summary of the literature on Proso millet and an overview of the present situation of cultivation in the growing regions of Sri Lanka (S.O. 1).
- **Chapter 3** explores the characteristics of rainfall and Proso millet growing season, trends of rainfall, long-term dry spells and farmer's crop husbandry strategies on Proso millet farming systems in Sri Lanka (S.O. 2).
- **Chapter 4** describes experimental details of the data sets used for model calibration and validation, and procedures for the calibration of the APSIM millet model for Proso millet and validation results for farmer fields in Sri Lanka (S.O. 3).
- **Chapter 5** evaluates the future climate of Proso growing region in Sri Lanka, the crop production sensitivity to climate variability and Proso millet yield projections for the mid-21st century (2040–2069) (S.O. 4 and 5).
- **Chapter 6** is the general discussion and conclusions of the study.

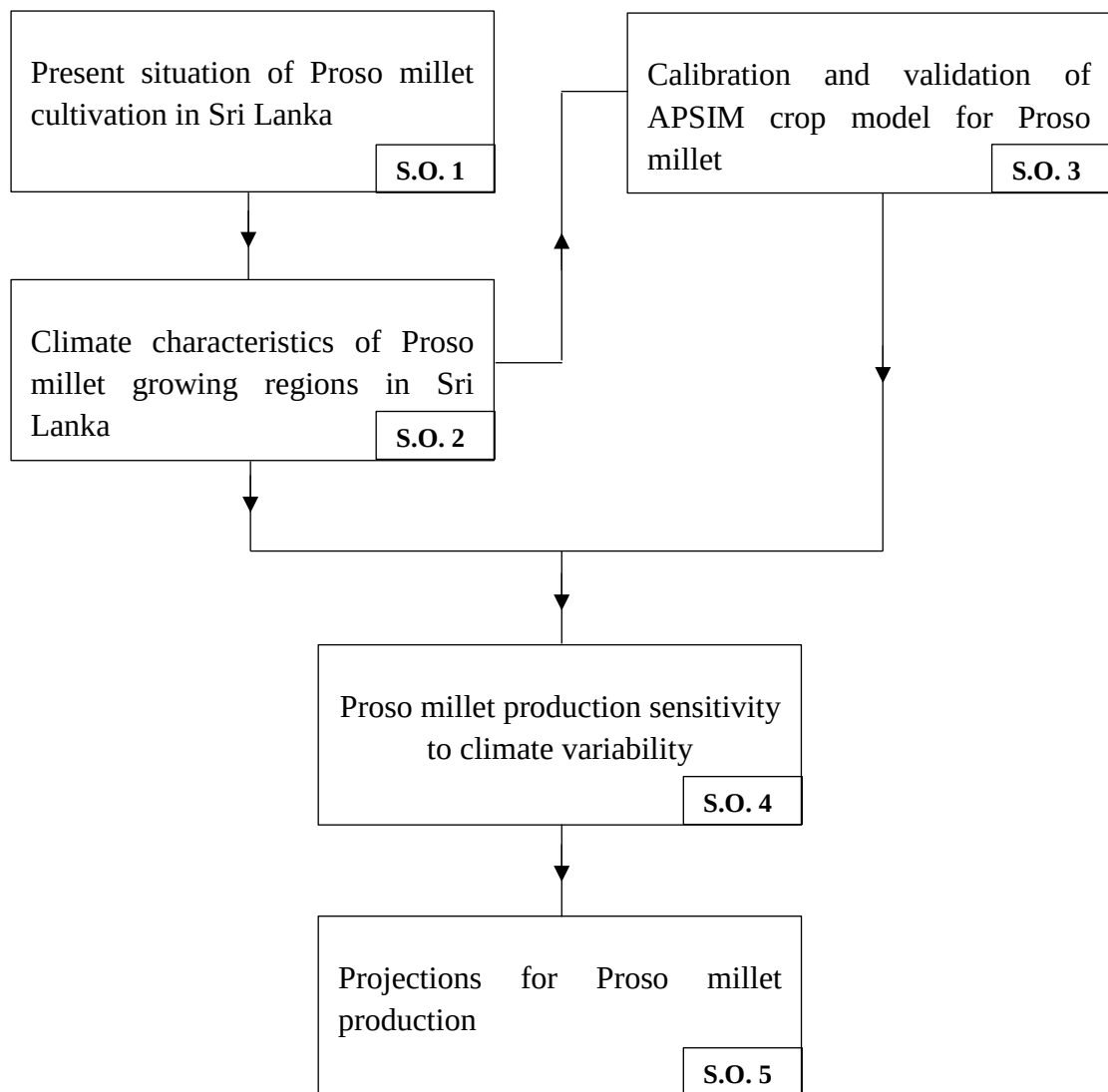


Figure 1.1. The outline of the thesis with specific objectives (S.O.) of the study.

Chapter 2

The present situation of Proso millet cultivation in the growing regions of Sri Lanka*

2.1. Introduction

Proso millet (*Panicum miliaceum* L.) is an under-researched important cereal that is cultivated in southern parts of Low Country Dry Zone (LCDZ - the characteristics will be described in Chapter 3 of the thesis) Sri Lanka. It is an exemplary underutilised crop that offers the possibility of multiple securities as food, nutrition, fodder, fibre, health and livelihood in future where rainfall might be less reliable (Ravi et al. 2010; Ačko et al. 2012; Millet Network of India 2014; Habiyaremye et al. 2017).

The demand and the cultivation of commercial/cash crops such as maize have increased in Sri Lanka and most of the traditional crops like Proso millet remain underutilised (Malkanathi 2017). It was reported that various crop varieties fulfilled the food requirements of Sri Lankan people in the past, however, these crops have been displaced or are underutilised due to several reasons including the lack of awareness of farmers on the importance of these crops as a food source (Malkanathi 2017). Therefore,

* *The chapter based on the monograph of Proso millet:* Karunaratne AS. (Ed.) Proso millet (*Panicum miliaceum* L.)—Agronomy, Botany, Ecophysiology and Nutrition. Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka (ISBN 978-955-644-044-7) *and the conference paper:* Wimalasiri EM, Ashfold MJ, Walker S, Nissanka SP, Karunaratne AS. 2017. On-farm spatial variability of Proso millet cultivation in Moneragala and Hambanthota districts of Sri Lanka. Abstracts of the 6th International Conference of Sabaragamuwa University of Sri Lanka; May 3–5; Kandy, Sri Lanka. p. 127.

it is vital to find the importance and constraints of Proso millet cultivation from the farmers' point of view and their attitudes towards the cultivation.

Information on the history of Proso millet cultivation in Sri Lanka was not found in scientific literature, but according to folkloric stories, it has been a traditional cuisine from the ancient time. Further, farmers and their ancestors cultivated Proso millet for several generations. Being a traditional crop among subsistence farmers, farmer specific and different crop management practices can be observed in Proso millet fields. The exploitation of existing traditional knowledge and the great potential of Proso millet provide the platform for food and nutrition securities as a future crop that will directly contribute to the national development goals of Sri Lanka. Therefore, it is important to evaluate the present status of Proso millet cultivation and gather the indigenous knowledge of growers on Proso millet cultivation and use in growing regions of Sri Lanka.

Not being a cash crop/commercial crop in Sri Lanka, Proso millet has received less research attention. The present situation of cultivation in the country and different type of crop management practices have barely been studied and documented. Further, the effects of these management practices on the final yield have not yet been identified. In this Chapter, the focus is given on Proso millet cultivation in LCDZ Sri Lanka, where it is a potential crop to fight against the food insecurity among rural communities. Therefore, the purpose of this Chapter is to assess the current status of Proso millet cultivation in the growing regions of Sri Lanka using social survey procedure and harvest collection, to lay a foundation for assessing Proso millet's suitability to enhance the production in subsistence farming systems in a changing climate.

Within this chapter (a) section 2.2 summarises the literature on Proso millet morphology, uses and its suitability in the climate changing world and (b) and sections 2.3 – 2.5 describe, based on results from farmer surveys, the present situation of the cultivation in Moneragala and Hambanthota as growing regions in Sri Lanka. Section 2.6 concludes the content in Chapter 2.

2.2. Proso millet crop - review

In this section, the characteristics of Proso millet as a crop are reviewed based on the morphology, growth and environment requirements, health benefits and favourable characteristics as a future crop from the literature.

2.2.1. Background

Proso millet is a short duration (60 to 70 days) minor millet (Reddy et al. 2007) that is cultivated in subsistence farming systems of Africa, India (Habiyaemye et al. 2017) and drier parts of Sri Lanka. Farmers grow Proso millet as a subsistence crop with local landraces for dietary requirements as well as for income generation (Ghimire et al. 2018). The primary sources of demand are the rural farming population and people prefer it as a substitute for rice. Proso millet is cultivated as a rainfed crop in Sri Lanka (Department of Agriculture Sri Lanka – DOASL) during *Yala* season (details of the season and relationship to seasonal rainfall patterns are examined in Chapter 3). It is cultivated in the short fallow period after cereal-legume rotation in the Indian subcontinent and short growing season allows it to use in an intercropping system with legumes or oil seeds (Krishna 2013). Proso millet is also a good candidate in crop rotations to control weeds, disease and pest cycles (Heyduck et al. 2008).

Proso millet is one of the world's earliest domesticated cereals (Hunt et al. 2014) with evidence indicating that it has been cultivated for thousands of years in China, India

and Russia (Reddy et al. 2007). The ancestor of cultivated Proso millet is a wild type native to China and considered as an aggressive weed that is resistant to herbicides (Habiyaemye et al. 2017). Minor millets like Proso millet are cultivated in specialised agricultural niches (Seetharam et al. 2006). In Sri Lanka, it is found in one of the primitive agricultural systems known as *Chena*, grown as a rain-fed crop with minimum tillage and low inputs and also concentrated into the Dry Zone (Malkanathi 2017).

2.2.2. Morphology

Proso millet is a self-pollinating short-day plant (Baltensperger 2002). It is an annual grass that grows to a height of approximately 1 m and has a shallow fibrous root system and a hollow stem. Leaf arrangement is alternate and both stem and leaves are covered with short hairs. Open panicle inflorescence is about 45 cm long and possesses partly self and partly cross-pollinated flowers. Oval shaped tiny seeds (2.5–3.0 mm in diameter) are varying in colour; white or creamy-white, red or yellow, grey, brown or black (Lágler et al. 2005; Reddy et al. 2007; Krishna 2013; Habiyaemye et al. 2017). Morphological features of Proso millet plant are shown in Figure 2.1.

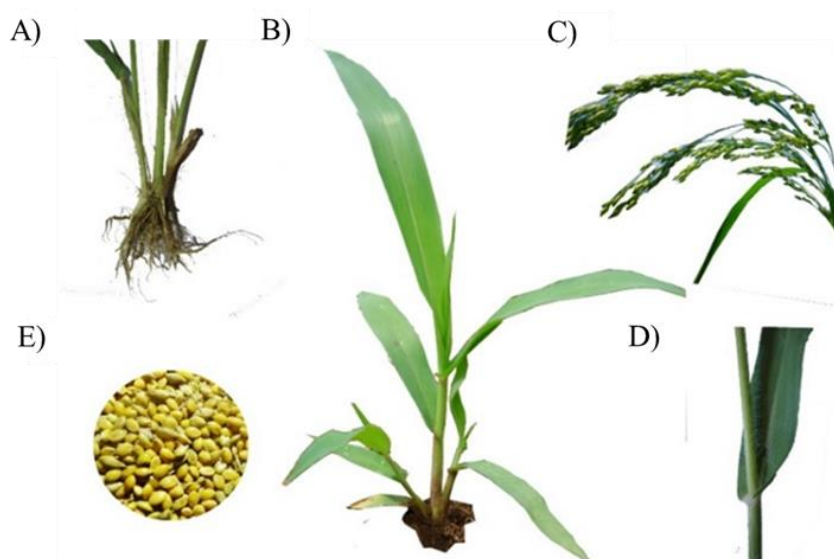


Figure 2.1. Morphological features of Proso millet (A). Stem and root system, (B). 14 d old plant, (C). Panicle, (D). Leaf sheath and blade and (E). Seeds.

2.2.3. Growth and environmental requirements

Proso millet needs warm temperature for seed germination and development (Habiyaemye et al. 2017). Their seeds germinate well in the temperature range of 20 to 30 °C (Baltensperger 1996). It is a crop with low water requirement (Baltensperger 2002; Léder 2004; Lyon et al. 2008; Changmei and Dorothy 2014). It survives and gives yield under conditions with annual rainfall as little as 300 mm (Changmei and Dorothy 2014) and in the range of 200 – 450 mm (Krishna 2014).

Proso millet grows in a wide range of soils including sandy loam, slightly acidic and saline soils (Changmei and Dorothy 2014) but poorly grows in coarse sandy soils (Williams et al. 2007) and under waterlogged conditions (Seghatoleslami et al. 2008; Hunt et al. 2011). The optimum pH range for seed germination is 5.5 to 6.5 (Baltensperger 1996; Lyon et al. 2008) and grows well on neutral or acidic soils with pH 6.0 (Krishna 2013). Proso millet shows iron chlorosis symptoms when the pH is above 7.8 (Habiyaemye et al. 2017).

2.2.4. Health benefits and uses

Proso millet is a food plant and cropped mainly for human consumption as well as a livestock feed. Its nutritional composition is superior to other cereals and rich in protein content (protein content >11%) (Saleh et al. 2012; Amadou et al. 2013; Krishna 2013) and it is used in Sri Lankan folkloric medicine for snakebite poisoning (Department of Agriculture Sri Lanka; Nuwan et al. 2016). In Ayurveda, congee prepared from Proso millet is given for acidity and biliousness (Nuwan et al. 2016). Proso millet is gluten-free, therefore, it is an excellent option for people with coeliac disease and other gluten intolerances (Amadou et al. 2013; Nuwan et al. 2016). It is rich in beneficial nutrients such as the high amount of fibre, B-complex and some other vitamins (Reddy et al.

2007). The availability of essential amino acids such as leucine, isoleucine, and methionine are higher than wheat (Kalinova and Moudry 2006). The concentrations of low density lipoprotein (LDL) cholesterol were lower in Proso millet, therefore, it can prevent cardiovascular diseases (Lee et al. 2010). Phytochemicals such as phytic acid, phytate and benzoic acids found in Proso millet is believed to lower cholesterol and reduce cancer risks (Nuwan et al 2016). Proso millet also has good potential as a raw material for malting purposes (Zarnkow et al. 2007). It is reported that Proso millet whole grains are rich sources of phenolic compounds and show different antioxidant, ion chelating, and reducing powers (Chandrasekara and Shahidi 2010).

Other than the human consumption, Proso millet is frequently used in the livestock industry to feed cattle, sheep, swine, poultry and especially pet birds (Baltensperger 1996; Lyon et al. 2008). The availability of most of the required nutrients in Proso millet makes them suitable for large scale exploitation in the production of various food products such as snacks, baby foods, porridge, wine and dietary foods (Subramanian and Viswanathan 2007; Liu et al. 2012).

2.2.5. Proso millet – a crop for the future

Proso millet is a crop with low water requirement (Baltensperger 2002; Lyon et al. 2008; Changmei and Dorothy 2014) and has been highlighted as a crop that is particularly useful in a climate where rainfall might be less reliable (Swaminaidu et al. 2015). Proso millet utilises moisture more efficiently (Habiyaemye et al. 2017) as it uses less than half of water to produce one kilogram of dry matter compared to wheat and maize (Ačko et al. 2012). Proso millet, a hardy crop, is resilient to adverse effects of agro-climatic variations such as soil infertility and rainfall scarcity. Excellent

adaptability of these crops plays an important role in marginal agriculture, which is commonly practised in hilly and semi-arid India (Ravi et al. 2010).

The growth of Proso millet further into the northern hemisphere (up to 54° latitude) than the other millets (Baltensperger 1996) suggests its ability to withstand a wide range of environmental conditions. The short growing season of the crop allows cultivation in a broad range of altitudes (Kalinova and Moudry 2006), climatic and soil conditions (Baltensperger 1996). Proso millet can provide a reasonable yield in degraded soils and under unfavourable climatic conditions (Nirmalakumari et al. 2008). Salt tolerability of Proso millet genotypes suggests it as an alternative crop for salt stressed areas (Liu et al. 2014).

Rapid maturity nature of Proso millet helps to skip the drought sensitivity (Baltensperger 1996). Reduction of the height of the primary stem, alter vegetative growth and ceases to flower are drought resistant characteristics of the plant (Changmei and Dorothy 2014). As a C₄ crop, Proso millet fixes carbon dioxide efficiently under drought, hot temperatures, and limited nitrogen and CO₂ due to a low transpiration ratio of the crop (Habiyaemye et al. 2017). The available literature emphasises Proso millet will be an ideal crop in future decades where climate unfavorability is a critical issue causing severe food crisis.

2.2.6. Proso millet germplasm

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) conserves a total of 842 Proso millet germplasm accessions from 27 countries and 358 with unknown origin. The highest number of accessions were found from former USSR (128) and the lowest of one accession from 9 countries. Two Sri Lankan accessions are available at ICRISAT. Proso millet was classified into decumbent, erect and erect-

geniculate based on the growth habit. Sri Lankan accessions were erect but decumbent types were dominant followed by erect, among accessions across the world. The two accessions recorded from Sri Lanka were the tallest (97.5 cm) among all (Reddy et al. 2007).

Improved Proso millet varieties are available for farmers in different parts of the world. The *Huntsman*, *Earlybird*, *Horizon*, *Sunrise*, *Sunup* and *Dawn* are some of the common varieties in the United States that are different in characteristics and performances (Lyon et al. 2008). There are two types of Proso millet according to the grain size: as smaller and larger types available in Sri Lanka (DOASL-www.agridept.gov.lk). The smaller type lacks uniformity in maturity and therefore, it causes heavy grain loss due to shattering. Proso millet with larger grains are more uniform in maturity and have a potential of yielding up to 4 t ha⁻¹ within 60 days. The Department of Agriculture recommends MS 1491, AC 254 and V 62 as promising varieties (DOASL).

2.3. Methodology

As detailed below, a combination of past data, on-farm field survey, field observations and field sampling approaches were used to study the present situation of Proso millet cultivation in growing regions of Sri Lanka.

2.3.1. Past data on Proso millet Production

Past data on Proso millet land extent and harvest in Moneragala and Hambanthota districts were collected from Hector Kobbekaduwa Agrarian Research and Training Institute (HARTI) for the 1980 – 2016 period (*Yala* season). The data were initially recorded by the Department of Census and Statistics Sri Lanka. However, the data were missing for the year 1989, 2002 and 2012 in Moneragala and year 2008, 2009, 2012 and 2014 in Hambanthota districts.

2.3.2. Soil sample collection and analysis

Soil samples were collected during March 2015 from cleared fields that were ready to cultivate. The rainfall pattern during soil sample collection will be shown in Figure 3.5. Samples were collected from 12 locations that covered the whole Proso millet growing area in the study. In each location, soils were sampled down at three depths; at 0 – 10 cm, 10 – 20 cm and 20 – 30 cm using a manual auger. Sampling was carried out from three random replicates in each field. Soil moisture content, bulk density, pH, electrical conductivity, colour, texture and total nitrogen were measured in each sample. Soil analysis procedures are summarised in Appendix 1.

2.3.3. Harvest collection

Proso millet plants were harvested from 41 farm fields covered by the survey (section 2.3.5), at harvesting stage during 23rd May to 4th June 2015. Harvest could not be collected from all the 50 farmers surveyed because all the Proso millet fields were harvested within a few days. One square meter quadrant was used to select three locations in the farmers' fields and samples were collected avoiding boundaries, foot paths, stones, water streams and big trees. Uprooted plants were sun dried for 8 hours and stored in paper bags. Yield analysis was performed for the harvested samples. The number of Proso millet plants and panicles in one square meter area were counted in each sample.

2.3.4. Yield analysis

To find the biomass and yield data, first, the total weight of the sample was measured, then 15–20% of subsample was taken for dry weight measurement (Van Oosterom et al. 2002). Plants were separated into roots, stems, leaves and panicles. Panicles were further separated into seeds and stalk. Leaf sheath was counted in to stem based on the

method followed by Van Oosterom et al. (2002). Plant parts were oven dried at 80 °C for 48 hours. Oven dried samples were cooled in a desiccator for two hours and the dry weight of each sample was weighted. Seed weight was obtained from three samples of 100 grains and seed number was calculated using seed weight and grain yield (Van Oosterom et al. 2002).

2.3.5. On-farm field survey

Grey literature and informal discussions with the Department of Agriculture helped to select the study area. A field survey was conducted during March–June 2015 (*Yala* season) in Proso millet growing regions of Moneragala and Hambanthota (6.41 – 6.44°N, 81.08 – 81.12°E) districts of Sri Lanka (Figure 2.2).

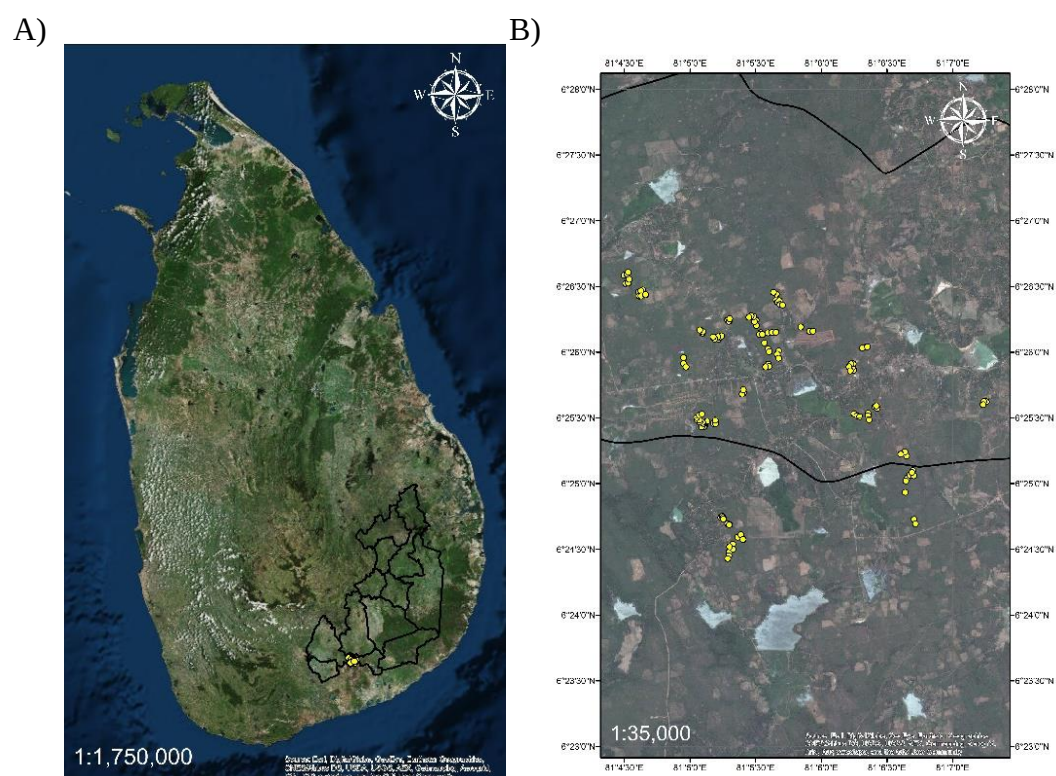


Figure 2.2. Map of Proso millet harvest collection area (A) and distribution of farm fields during *Yala* 2015 (B). Moneragala district was highlighted (A) as the major Proso millet growing district in Sri Lanka. Black lines (B) are borders of divisional secretariats and yellow circles are Proso millet farm fields.

The study area belongs to the LCDZ of Thanamalwila divisional secretariat (DS) division (Moneragala) and Lunugamwehera DS division (Hambanthota). The area was selected because farming Proso millet is a key feature of most people's livelihood in the area. Fifty farmers were selected using the simple random sampling technique.

The researcher administered pre-tested questionnaires (Appendix 2) were used to collect data on sowing and harvesting dates, crop selection and management practices, constraints, opportunities and attitudes of farmers. Moreover, a few group discussions were conducted with officials from the Department of Agriculture Sri Lanka, Agrarian office Thanamalwila and Proso millet farmers to gain in depth information on the cultivation and for the preparation of the questionnaire.

2.3.6. Data analysis

The Prism (Version 7.03) software was used to perform the analysis of variance (ANOVA) and regression analysis while both Prism and Microsoft Excel packages were used for graphing. The logit regression model was used to analyse the probability of Proso millet production as influenced by age, gender, education, occupation of farmer and field size. The analysis was performed using Stata (version 14.0) software.

2.4. Results

2.4.1. Past data on Proso millet production

The data collected from HARTI suggests the land extent under Proso millet cultivation was declining rapidly in both districts and shows an extraordinary pattern (Figure 2.3A). Proso millet extent for the 1980–1994 period was 482 ha (SD 312 ha) in Moneragala and 105 ha (SD 77 ha) in Hambanthota district. In contrast, the extent for 1995–2016 was 13 ha (SD 15 ha) and 7 ha (SD 12 ha) in respective districts. Proso

millet is a minor crop in Sri Lanka and the cultivation do not receive much attention from the Department of Agriculture and field agricultural officers. The very low extent recorded by the Department of Census and Statistics may be due to low attention from agricultural authorities. However, observation of Proso millet fields during the 2015 growing season, survey results (section 2.4.2) and discussion with farmers revealed that the land extent is higher than the amount reported by HARTI.

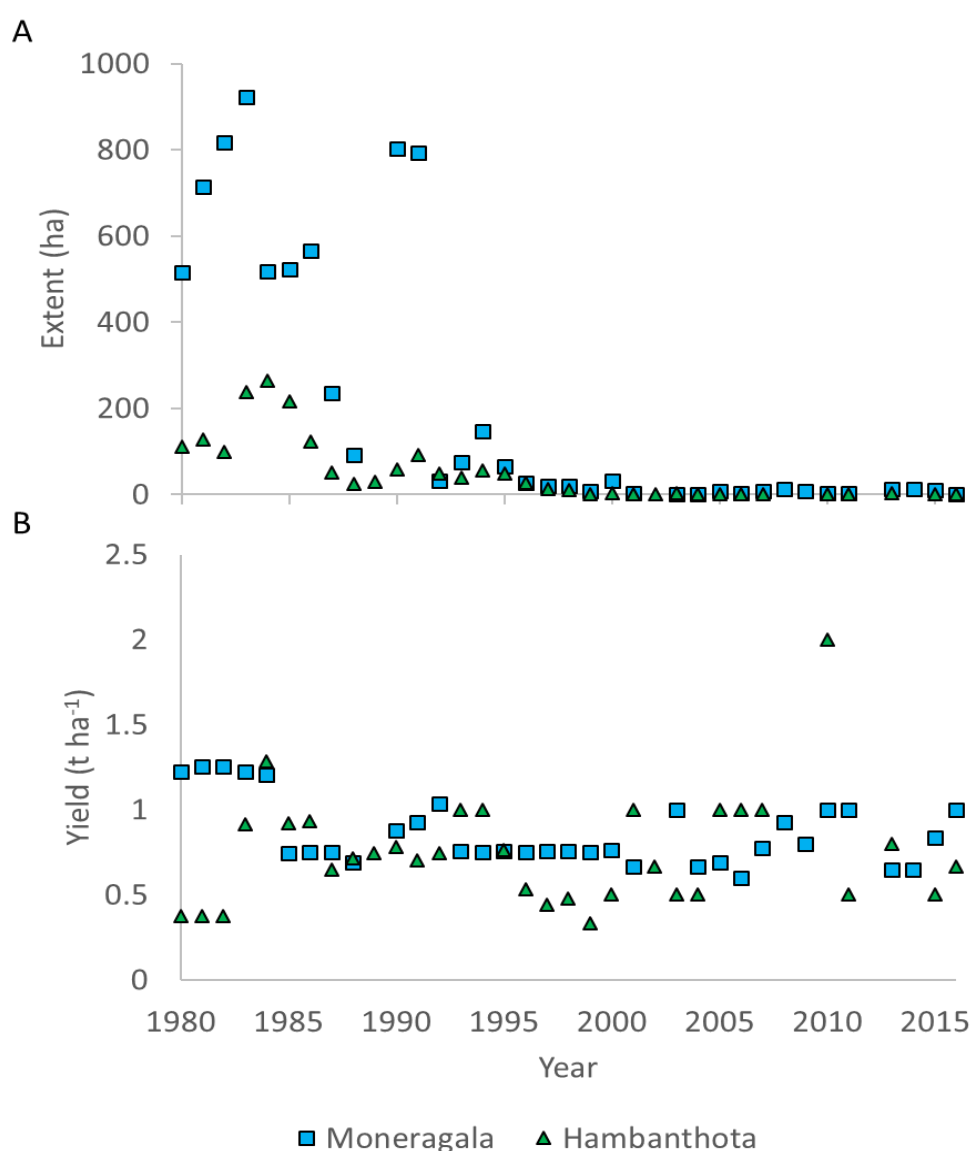


Figure 2.3. Variation of Proso millet (A) land extent and (B) yield during the 1980–2016 period reported by Hector Kobbekaduwa Agrarian Research and Training Institute (HARTI).

The yield was calculated by HARTI from the production and land extent (Figure 2.3B). The average yields reported for the 1980–2016 period were 0.86 t ha⁻¹ (SD 0.19 t ha⁻¹) in Moneragala and 0.75 t ha⁻¹ (SD 0.33 t ha⁻¹) in Hambanthota. These yields are far below the values observed in this work for 2015 *Yala* season (described in section 2.4.4). The officially recorded lower land extent and the production in recent years (after 1994) may be associated with the low attention from agricultural authorities due to the introduction of commercial crops like maize.

2.4.2. Soil properties in the Proso millet growing region

The soil properties of Proso millet fields during 2015 *Yala* season are summarised in Table 2.1. The mean bulk densities were 1.33±0.13 gcm⁻³ (0–10 cm), 1.30±0.11 gcm⁻³ (10–20 cm) and 1.32±0.10 gcm⁻³ (20–30 cm) (Table 2.1). The bulk densities of different soil layers were not significantly ($p > 0.05$) different while the values were significantly different ($p < 0.05$) among fields according to the Kruskal-Wallis non-parametric analysis of variance. The moisture content of the soil was 22±2 % (0–10 cm), 22±2 % (10–20 cm) and 21±2 % (20–30 cm), and they were not significantly different ($p > 0.05$) among layers. However, the soil moisture content was significantly different ($p < 0.05$) among farmer fields.

The mean soil pH was 6.62±0.17 (0–10 cm), 6.62±0.18 (10–20 cm) and 6.67±0.22 (20–30 cm) and it ranged as 6.46 to 7.00 (0–10 cm), 6.35 to 6.93 (10–20 cm) and 6.43 to 7.11 (20–30 cm) (Table 2.1). Generally, the soil was slightly acidic and close to the neutral value (pH =7) while it was higher than 7 in one occasion only. The pH was significantly different ($p < 0.05$) among fields. A higher variation was observed in soil electrical conductivity (EC) as it ranged from 6.43 to 81.00 $\mu\text{S cm}^{-2}$ among all the tested

soil layers. The electrical conductivity of soil was significantly ($p < 0.05$) different among layers but it was not significantly different ($p > 0.05$) among fields.

It was found that sand percentage of the soil (ranged from 78.0 to 90.5%) was high in all the layers but decreased with the increment of the depth (Table 2.1). The percentage of sand in the soil was significantly different ($p < 0.05$) among layers, but not among the fields ($p > 0.05$). This may be a reason of flooding in rainy periods that removes silt and clay particles in the top soil. However, the soils in the Proso millet growing region contained comparatively higher clay content (ranged from 5.0 to 16.5%) than silt (2.0 to 9.7%). Generally, the soils were 'loamy sand' and 'sandy loam' according to the USDA soil textural class. Soil total nitrogen ranged in three soil layers as 0.20 to 0.93% (0–10 cm), 0.08–0.80% (10–20 cm) and 0.09 to 0.69% (20–30 cm) (Table 2.1). Total soil nitrogen was significantly different ($p < 0.05$) among fields, but not among the layers ($p > 0.05$).

Out of the studied soil properties, only bulk density had a significant ($p < 0.05$) relationship with the yield according to non-parametric Spearman correlation ($r = 0.43$) analysis.

Table 2.1 Summary of measured soil properties of farmers' fields in the study area during *Yala* 2015

Layer (cm)	BD (g/cm ³)	Moisture content (%)	pH	EC (μS /cm)	Texture			USDA textural class	N (total) (%)	Munsell colour		
					Sand (%)	Clay (%)	Silt (%)			Hue	Value	Chroma
0–10	1.33±0.13	22±2	6.62±0.17	44.61±18.56	86.55±3.19	8.37±2.89	5.09±1.78	Loamy sand	0.50±0.23	5.97±1.30 YR	4.5	1.6
10–20	1.30±0.11	22±2	6.62±0.18	29.80±9.83	85.32±3.27	10.54±2.29	4.14±1.39	Loamy sand	0.40±0.22	5.43±1.39 YR	4.5	1.5
20–30	1.32±0.10	21±2	6.67±0.22	28.63±14.74	81.91±2.96	12.90±2.52	5.19±1.05	Sandy loam	0.29±0.18	4.80±1.12 YR	4.8	1.5

BD = Bulk density, EC = Electrical conductivity

2.4.3. Proso millet plant and panicle density

Proso millet samples collected from 41 farm fields showed a wide range of plant and panicle densities (Table 2.2). An average number of plants per one square meter was 217 ± 94 (SD) with the range of 61 – 601 plants m^{-2} . The highest number of plants within one square meter was approximately 10 times higher than the lowest value and 3 times higher than the mean value. Panicle density also followed the same pattern with a higher deviation (mean 473 ± 132). The highest panicle number was recorded from the field with the highest plant density, but the lowest panicle number was not from the least density field.

Table 2.2. Observed and potential seed rate, plant density, yield and harvest index among Proso millet fields in the study area during Yala 2015 (n = 41)

Parameter	Observed values		Recommendation*
	Range	Mean	
Seed rate	10–25 kg ha ⁻¹	15±4 kg ha ⁻¹	5–6 kg ha ⁻¹
Plant density	61–601 plants m ⁻²	217±94 plants m ⁻²	33–44 plants m ⁻²
Panicle density	122–768 panicles m ⁻²	473±132 panicles m ⁻²	—
Yield	470–1956 kg ha ⁻¹	1180±345 kg ha ⁻¹	4000 kg ha ⁻¹ **
Harvest index	0.25–0.38	0.32±0.03	—

* DOASL

** Under recommended fertiliser usage of Urea - 175 kg ha⁻¹, Concentrated Super Phosphate - 50 kg ha⁻¹ and Muriate of Potash 50 kg ha⁻¹ (DOASL)

The mean plant density is far above the recommended plant number (33–44 m⁻²) by DOASL which is a seed rate of 5–6 kg ha⁻¹ while farmers in this area broadcast about 10–25 kg ha⁻¹ (Table 2.2) seeds making highly uneven fields in terms of spatial plant distribution. It seems that maintaining a very high plant density is an option adopted by Proso millet farmers in the area to protect against the damage of the crop related to rainfall and animals (birds and elephants). Proso millet is a poor competitor when compared with other plants, therefore weeds grow quickly in the fields (Berglund 2007). Discussion with farmers revealed that higher plant density avoids the weed problem in Proso millet fields.

2.4.4. Observed yield in the study area

The yield of Proso millet samples collected from farmers' fields varied from 0.470 t ha⁻¹ to 1.956 t ha⁻¹ with the mean of 1.180 t ha⁻¹. Mean yield was lower than the potential yield of 4 t ha⁻¹ (DOASL). Proso millet yield was lower than 1.0 t ha⁻¹ in 31.7% of farmers' fields indicating widespread low yields of Proso millet in the study area for 2015 growing season. However, the average yield was higher than the past data (0.86 t ha⁻¹ in Moneragala and 0.75 t ha⁻¹ in Hambanthota) collected from HARTI (section 2.4.1). Even Proso millet fields vary in plant density, the highest yield was not from the highest plant density category (Figure 2.4). The highest yield was from 326–350 plants m⁻² category but the percentage of farm fields in this plant density category was 2.44%. The harvest index determined by the ratio of grain yield to above ground biomass ranged from 0.25 to 0.38 with a mean of 0.32 (Table 2.2).

2.4.5. Effect of plant density on yield components of Proso millet

Regression analysis was conducted to determine the relationship between plant density with yield, non-grain above ground biomass, harvest index and panicle density (Figure

2.5 A–D) of Proso millet. The significance of the deviation of regression slope from zero was analysed for the linear trend line and a curve was fitted with nonlinear regression because linear regressions were not powerful (R^2 ranged from 0.28 to 0.35) to study the relationships. Other factors such as climate and soil were omitted in the analysis.

Regression analysis revealed that Proso millet yield (kg ha^{-1}) and non-grain above ground biomass (kg ha^{-1}) have significant ($p < 0.05$) positive relationships with plant density. The slope of the positive significant ($p < 0.05$) regression is higher for panicle density than for the yield and the biomass. High Proso millet plant density is likely to be accompanied by an increment in the panicle density. The scatter plot (Figure 2.5A) showed that higher grain yield was concentrated near average plant density (217 plants m^{-2}). Harvest index showed a positive relationship with the plant density, but it was not significantly different ($p > 0.05$).

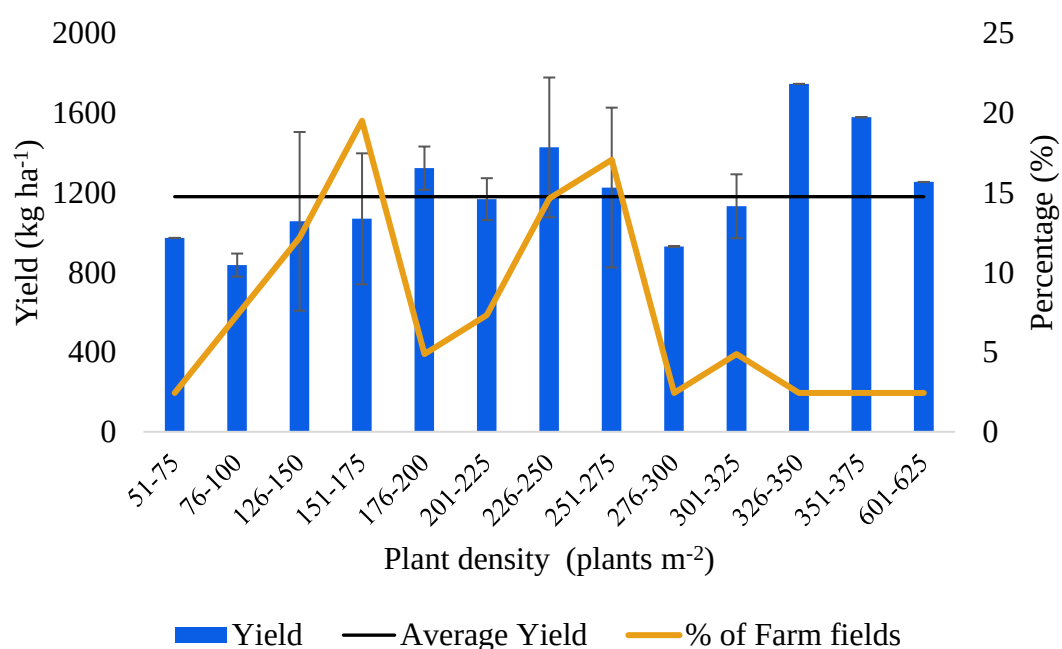


Figure 2.5. Variation of Proso millet plant density and their yield in the study area in Moneragala and Hambanthota districts during Yala 2015 (n = 41)

Non-parametric Spearman correlation was performed to study the relationship of plant density with the Proso millet yield components. It was found that the increment of plant density significantly ($p < 0.05$) decreased panicles per plant ($r = -0.71$), seeds number per panicle ($r = -0.41$) and grain yield per plant (grams) ($r = -0.66$). The panicle density (m^{-2}) showed a positive significant ($p < 0.05$) relationship with the plant density ($r = 0.72$). Decreasing weight of grain mass (mg) ($r = -0.06$) was not significantly different ($p > 0.05$) with the plant density. However, a weak correlation was observed in all the parameters with a low correlation coefficient.

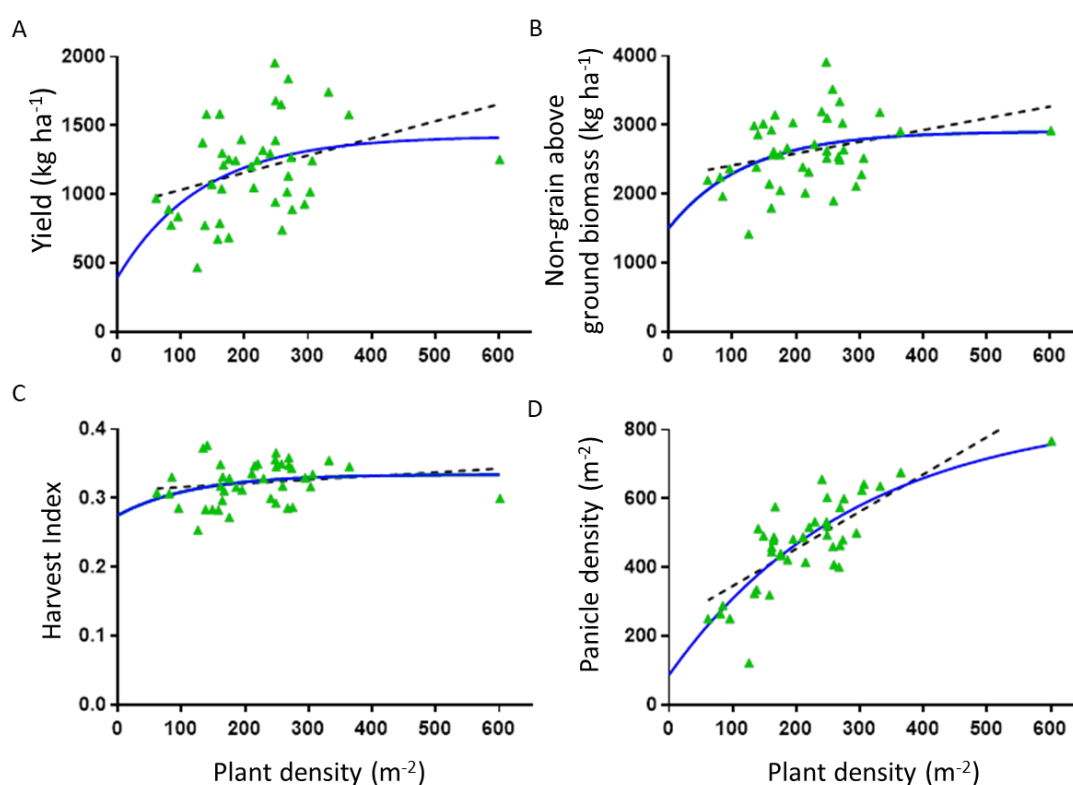


Figure 2.5 The relationships of Proso millet plant density with (A) yield (kg ha^{-1}), (B) non-grain above ground biomass (kg ha^{-1}), (C) harvest index and (D) panicle density (m^{-2}). The dashed line (black) is the linear regression and the blue line is the fitted nonlinear regression curve.

2.4.6. Summary of survey results

Out of fifty farmers on where the study was conducted, 80% belonged to Moneragala district while the rest of the fields (20%) were from Hambanthota district. The area covered by the survey was considered as Proso millet growing region in this chapter and no attempt was made to differentiate the characteristics in two districts.

Demographic characteristics of interviewed farmers

Most of the interviewed farmers in Proso millet growing region belong to the 46–55 age category (42%) followed by 36–45 group (28%). Only 2% of farmers are above 65 years old. Out of the interviewed Proso millet farmers in the area, only 6% were female farmers. Land preparation is a time and labour consuming hard work (described under ‘Agronomic practices’ in this section) that is considered difficult for females. Therefore, most of the farming activities are done by male farmers and they own Proso millet fields. But females are largely involving in the harvesting of Proso millets. Demographic characteristics of the study area are summarised in Table 2.3.

Table 2.3. Demographic characteristics of Proso millet farmers in the study area during Yala 2015 (n = 50)

Variables	Percentage
<i>Age</i>	
Below 35	12
36–45	28
46–55	42
56–65	16
Above 65	2
<i>Gender</i>	
Male	94
Female	6
<i>Educational level</i>	
No formal education	4
Up to grade 5	26
Up to grade 8	40
Up to grade 11	24
Up to Advance level	6
Degree	0
<i>Main occupation</i>	
Farming	92
Government	4
Other	4

Size of the Proso millet fields

Farm fields that were used to cultivate Proso millet ranged from 0.20 to 2.23 ha (0.5 to 5.5 acres) with an average of 0.82 ha (SD 0.48 ha). Most of the fields (50%) belong to 0.51–1.00 ha category (Figure 2.6). Percentage of farm fields decreased with the increment of land size and 76% of fields are less than 1 ha. Only 6% of fields are equal to or higher than 2.01 ha. Farmers with a comparatively larger farm field (normally more than 1 ha) do cultivation inside forest areas because they have enough space there. The number of fields with more than 0.81 ha (2 acres) in size is almost similar for Proso millet (52%) when compared with other underutilised crops (48%) in Moneragala district, Sri Lanka (Malkanathi 2016).

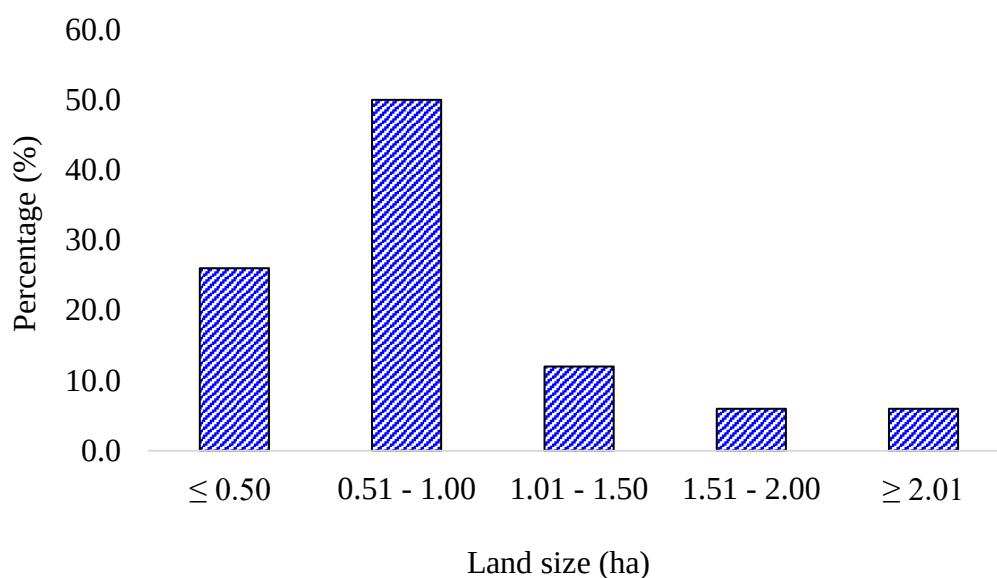


Figure 2.6. Variation of Proso millet field size in the study area during *Yala* 2015 in Moneragala and Hambanthota districts during *Yala* 2015 (n = 50)

Seed sources

Proso millet farmers use different seed sources as; seeds from the previous harvest on which they kept a portion for seed purpose, exchange with other farmers, get as donations and buy from a shop or another Proso millet farmers. Out of all, 38% of farmers use their own seed from the previous harvest for the cultivation. Normally, most of the farmers who cultivate other crops such as paddy and finger millet in the area keep a portion from harvest for seed purposes. New farmers and farmers who had to sell everything due to financial issues, lack of proper storage facilities and seeds infested with weeds (not good to keep for another generation) have to buy seeds (58%). Merchants in shops sell seeds as a business and some other farmers sell excess seeds and to get extra money because the price of seeds (LKR 200–300 per kg) are higher than the raw Proso millet (LKR 90–150 per kg). Only 2% of farmers each exchanged and donated seeds. The farmers exchanged Proso millet seeds for finger millet (*Eleusine coracana*) seeds. Sources of seeds in Proso millet growing region are shown in Figure 2.7.

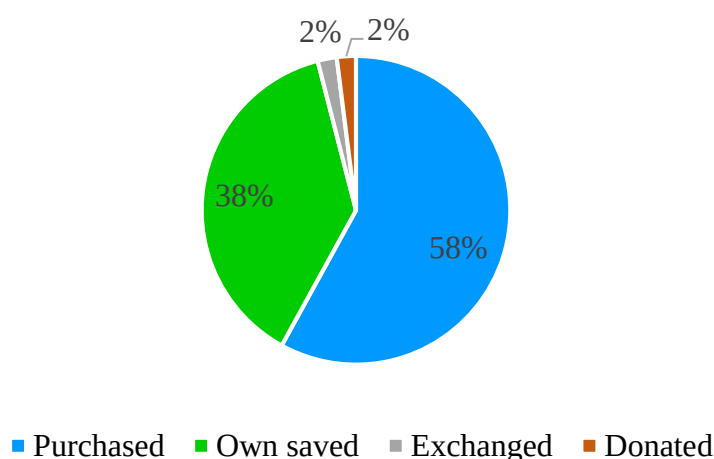


Figure 2.7. Different seed sources of Proso millet cultivated in the study area in Moneragala and Hambanthota districts during Yala 2015 (n = 50)

Proso millet varieties

Most of the farmers (92%) know that Proso millet varieties that existed in the past but have disappeared or replaced by other varieties. One famous variety that was existed is “*Kalu meneri*” that has black seeds. None of the varieties released by the Department of Agriculture Sri Lanka was available in the farmer fields by their names. Only one farmer in the area used Indian Proso millet (the name given by merchants) that has bigger seeds. These plants are bigger and stronger than the normal Proso millet. Discussions with farmers revealed that farmers do not like bigger seeded Proso millet because these plants are easily attracted by birds.

Farm inputs

Organic matter that was incorporated during land preparation is the major nutrient source (used by 100% of farmers) for Proso millet cultivation in the study area. Very few farmers (4%) add chemical fertiliser (urea as a nitrogen source) for Proso millet fields. Farmers buy chemical fertiliser for paddy cultivation at a subsidised rate from the government fertiliser subsidy scheme and they will not spend money on fertiliser for Proso millets. They applied the excess fertiliser that was saved from the amount received through the fertiliser subsidy scheme for paddy. The two farmers who used urea for their cultivation apply fertiliser during sowing and in the vegetative stage (3–4 weeks after sowing). Only one farmer prepared compost in his field and applied to Proso millet field.

Usage of Proso millet

Most of the Proso millet farmers (48%) did not keep seed for the next season and sold everything, indicating Proso millet is a cash crop to subsistence farmers in the study area. Some others (42%) kept less than 25% of the harvest for seed purpose while 10%

of farmers kept 26–50% of harvest for seed. Some of the farmers stored seeds to sell in the next season because they can get more money by selling seeds than the harvest. The weed free portion of seeds is kept by themselves for cultivation in the next season.

Agronomic practices

Proso millet fields were prepared by either using machinery such as tractor-drawn plough (44%) or manually (56%). Broadcasting was the universal Proso millet planting method (100%) and none of the farmers in Moneragala and Hambanthota districts practised row seeding. Amount of seeds for broadcasting vary from one farmer to another leading uneven plant density (describe in section 2.4.3).

Different broadcasting methods were observed among Proso millet fields in the area. Normally, farmers clear the fallow vegetation, burn it, and broadcasted seeds to the field with residues, then covered by mamoty or tractor-drawn plough. Some farmers broadcasted seeds in pre-ploughed lands and covered by plough (nine-tine tiller) and branches with leaves attached to the tractor. Some of them broadcasted seeds in a ploughed land and did not cover them, but allow rain to cover seeds by splashing effect of rain drops. This will wash out seeds and gaps can be seen in lots of places. Some other farmers followed ‘dry seeding method’ i.e. broadcast seeds without any rain either on the same day or day before. Ants, squirrels and birds carry seeds and create gaps in the fields.

Farmers did not have much work after the planting until the ripening stage since 94% of farmers did not practice weeding. A competing weed (locally known as “Atawara”—*Panicum repense*) in the family *Panicum* with a similar morphology was commonly found in Proso millet fields in Sri Lanka, causing a big problem of seed contaminations. But farmers did not tend to control or remove them from their fields. Thinning was also

not practised in Proso millet fields. None of the farmers used insecticides or other agrochemicals to control pests and diseases since these conditions were rarely reported. All the fields (100%) were rainfed and artificial irrigation was not practised for Proso millet in the study area.

Since Proso millet is a common bird feed, these fields are attracted by birds of different types from the grain filling stage. Farmers chased away them and protect their fields in the night from elephants and wild boars. Harvesting Proso millet was a labour-intensive activity and they hired labourers from other areas than the family labour. All the fields (100%) were harvested manually by sickle. Only one farmer tried to harvest Proso millet by a machine developed by himself using a grass cutter, but it failed due to seed shattering.

Reasons to cultivate Proso millet

There were few reasons for farmers choosing to cultivate Proso millet in Moneragala and Hambanthota districts (Figure 2.8). All the farmers (100%) cultivated Proso millet because it generated high income. Farmers cannot cultivate other field crops or paddy due to low rainfall during *Yala* season (Chapter 3) and low water amount in tanks. So, cultivation of Proso millet is considered the best option since it does not need much water and care. The price of raw Proso millet (LKR 90–150 per kg) was more than three times higher than for rice. Due to the high income generated under harsh growing conditions, most farmers tend to cultivate Proso millet.

Cultivation was widely considered easy (78%) because it does not need intense land preparation, weeding, fertiliser application, irrigation and crop protection. Proso millet fields are only protected from birds after grain filling stage. It is an alternative crop for paddy and farmers cultivated Proso millet due to its importance as a food source (46%).

Some farmers cultivated them due to the medicinal properties (26%). Only 4% of farmers believed Proso millet will improve the soil.

Strengths and opportunities for cultivating Proso millet

The strengths and opportunities for cultivating Proso millet in the study region, cited in were drought tolerant nature of the crop, selling of excess production is available, land for cultivation is available, the soil is suitable and knowledge and skills of cultivation are available (Table 2.4). Tested statements on strengths and opportunities for Proso millet cultivation were significantly different (p value < 0.0001) among others according to Kruskal-Wallis non-parametric analysis of variance.

Most of the respondents (76%) considered Proso millet to have a potential in dealing with the effects of drought due to its ability to survive and produce yield during the low rainy period. The area receives a relatively low amount of rainfall throughout the year and during the growing season (Chapter 3). Farmers believed the crop is adapted to the drier conditions and climate variability experienced in the region.

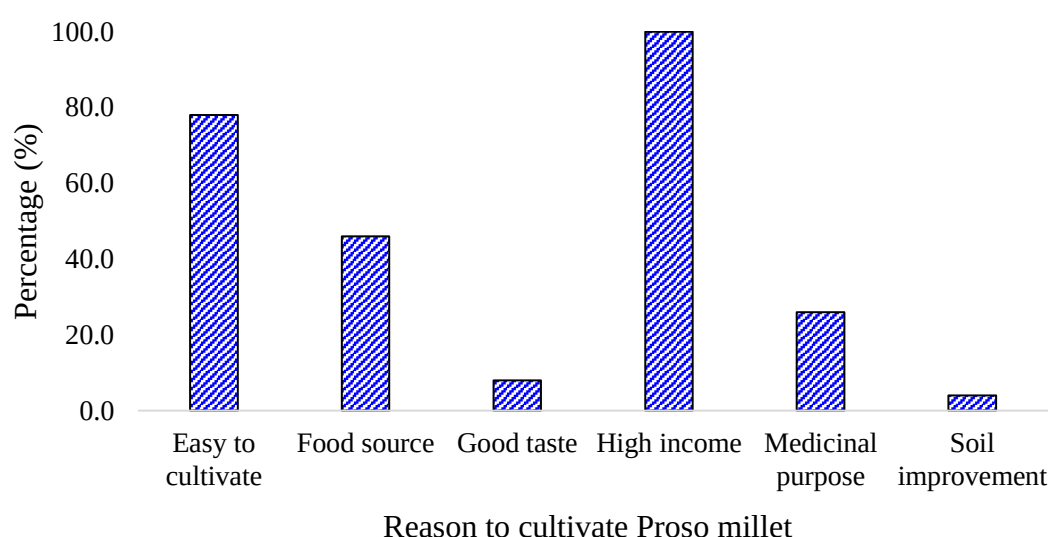


Figure 2.8. Reasons to cultivate Proso millet in the study area in Moneragala and Hambanthota districts (n = 50)

Proso millet farmers in the study area viewed Proso millet as a crop with great potential (74%) due to the availability of selling of excess production. This is because, in most of the farm fields, merchants come to the field of harvesting and buy the whole harvest. The harvest of remaining fields was being sold at the local market or shops/ near the roads to that were brought by people from other areas. But, the farmers cannot sell vegetables or their major crop paddy in this way due to the availability in other areas and high production. Availability of land (68%) and suitable soil (64%) were good strengths for improving Proso millet cultivation in the area. Further, their knowledge (42%) and skills (38%) on cultivation were also opportunities for Proso millet production.

Table 2.4. Summary of strengths and opportunities for cultivating Proso millet in the study area during *Yala* 2015 (n = 50)

Statement	Mean with SD	Remarks
Knowledge on cultivation is available	4.48±0.65	Agree
Skills on cultivation is available	4.44±0.79	Agree
Land for cultivation is available	4.08±0.67	Agree
Soil is suitable	3.66±0.67	Agree
Suitable climatic condition is available	3.12±0.98	Neither agree or disagree
Labour for cultivation is available	2.48±0.99	Disagree
Selling of excess production is available	3.50±0.86	Agree
Drought Tolerant	4.08±0.49	Agree

In general, the suitability of climate conditions belonged to the category of ‘neither agree or disagree’ as an opportunity, but it was found that 48% of respondents agreed as the available climate is an opportunity for Proso millet cultivation while 30% disagreed. This is mainly because some farmers had a bad experience in the destruction of Proso millet fields due to heavy rain and prolonged drought. A higher number of farmers agreed the climate was good because they cannot cultivate other crops during the period they grow Proso millet due to the very low rainfall during that part of the year. Labour availability was not an opportunity for the cultivation as farmers experience difficulties due to labour shortage, especially for the harvesting. Clearance of land, preparation and planting were mainly done by family members and the labour shortage is not viewed as an issue for those activities.

Constraints for cultivating Proso millet

Constraints for Proso millet cultivation identified by farmers were wildlife threat, no availability of knowledge on processing and value addition and lack of good quality seeds (Table 2.5). Results of Kruskal-Wallis non-parametric analysis of variance revealed that cited constraints for cultivating Proso millet were significantly different (p value < 0.0001) among others.

Wildlife threats were identified as a major challenge (58% of farmers strongly agreed and 38% agreed) for Proso millet cultivation while only 2% believed it was not a problem. Elephants and peacocks (harvesting stage) were the major animals that damage Proso millet. Even though farmers believed that they have skills and knowledge on the cultivation, lack of knowledge on the processing and value addition was another major constraint (68% strongly agree). Proso millet farmers sold their harvest to merchants and even did not know what happen to the harvest after selling. There are

different value-added products of Proso millet as bakery products and sweets, but farmers were not aware of them.

Lack of good quality seeds ranked as a lower ranked constraint (52% agreed and 22% disagreed) for the cultivation. Weeds (specially *Atawara*) were abundant in a lot of Proso millet fields and these seeds mixed with Proso millet seeds. Farmers use these mixed seeds for next season. Another important fact was Proso millet farmers use their own seeds for several generations and they are not improved varieties. Seed viability was low and farmers have to use a higher seed rate. The unavailability of good quality seeds is related to the negligence of the agricultural research community.

Table 2.5. Summary of constraints for cultivating Proso millet in the study area during Yala 2015 (n = 50)

Statement	Mean with SD	Remarks
Lack of good quality seeds	3.78±1.06	Agree
Knowledge on processing and value addition is not available	4.58±0.73	Strongly agree
Market facilities are not available	2.48±0.95	Disagree
There is a higher competition with modern commercial crops	3.10±1.04	Neither agree or disagree
There is a negative attitude of consumers towards underutilised crops	2.36±0.66	Disagree
Wildlife threats	4.52±0.65	Strongly agree

Also, farmers had to store seeds for one year and since they did not have good storage facilities, pests like rats damaged the seeds. Farmers who believed seed quality was not an issue, carefully used their own weed free seeds/ pure seeds, produce their own good quality seeds and give special care for weeds free fields.

Out of the interviewed farmers, 44% agreed that there is competition with commercial crops such as paddy and maize while 38% believed that there is no competition for Proso millet. This is because commercial/cash crops receive attention from both government (paddy) and private sector (maize). Commercial crop farmers receive seeds for low price, fertiliser (government subsidy for paddy) and good extension service that were not received by Proso millet farmers. But due to the higher market price, availability of market and ability to cultivate in the drier period, farmers (38%) believed that competition with commercial crops was not a constraint for Proso millet cultivation.

Farmers disagreed that there was a negative attitude of consumers towards underutilised crops like Proso millet (68%) and market facilities were not available (58%). Proso millet can be popularised due to the good attitude of consumers. The market facility was not an issue for Proso millet like crops since they are cultivated in specific regions and demand is high.

Attitudes of farmers towards Proso millet cultivation

Assessment of the Proso millet farmers' attitudes on cultivation and use of the crop are important for the future development of the crop. Therefore, their attitudes towards the importance of the Proso millet cultivation were assessed using ten statements that are summarised in Table 2.6. Tested attitudinal statements were significantly different (p

value < 0.0001) among others according to Kruskal-Wallis non- parametric analysis of variance.

According to the survey results, farmers strongly agreed that Proso millet cultivation was profitable (68%) and needs low water amount (68%). There were few inputs in the cultivation and Proso millet did not require good land preparation and crop protection. Therefore, the cost of production was low and the cultivation is profitable.

Table 2.6. Attitudes of Proso millet farmers towards the importance of cultivation in the study area during *Yala* 2015 (n = 50)

Statement	Mean with SD	Remarks
Proso millet cultivation is profitable	4.52±0.58	Strongly agree
Proso millet has nutritional value	4.44±0.50	Agree
Proso millet has medicinal value	4.32±0.51	Agree
Proso millet needs low cost for cultivation	3.94±0.47	Agree
Proso millet needs a low level of water	4.50±0.79	Strongly agree
Proso millet has less pests	3.70±0.58	Agree
Proso millet has fewer diseases	3.92±0.53	Agree
Proso millet contributes to the biodiversity	3.12±0.75	Neither agree or disagree
Proso millet helps for environmental protection	2.78±0.76	Neither agree or disagree
Proso millet can tolerate climate changes	3.60±0.90	Agree

Since farmers agreed that Proso millet has fewer pests (76%) and diseases (72%), the cost for agrochemicals were low. Because farmers had to use a lot of money for agrochemicals in paddy and vegetable cultivation. Farmers also agreed that Proso millet contains nutritional (56%) and medicinal values (64%) and they can tolerate climate change (52%).

A low number of farmers agreed that Proso millets contribute for the biodiversity (34%) and help for environmental protection (20%) while most of the farmers neither agreed nor disagreed with these two attitudinal statements (44% and 38% respectively). Overall, the positive attitudes of Proso millet farmers can be used to popularise the cultivation in the area.

2.4.7. Evaluation of factors affecting Proso millet production using on-farm field survey

The data gathered from the on-farm field survey and yield from harvest collection were used in this section to evaluate the demographic, crop-related and attitudinal factors affecting Proso millet production.

Logit model

The Table 2.7 summarises the results of the logit model that was used to analyse the probability of Proso millet production as influenced by demographic (age, gender, education level and occupation), crop management (type of land preparation and herbicide application) and other crop-related data (field size, soil type and seed source) for the 2015 growing season in the study area. It should be noted that a “unit” in Table 2.7 refers to the categories in the demographic data (Table 2.3) and the code given for other categorical data.

Table 2.7. Summary of logit regression results for yield in Proso millet growing area during *Yala* 2015

Variable	Coefficient	Standard error	p value
Age	0.49	0.49	0.32
Gender	-0.87	2.17	0.69
Education	0.85	0.66	0.20
Occupation	1.26	1.13	0.27
Field size	2.71	1.49	0.07
Soil type	-0.46	0.66	0.49
Seed source	0.79	0.58	0.17
Type of land preparation	2.41	1.05	0.02
Herbicides before sowing	-0.61	0.94	0.52

Out of the tested variables, type of land preparation had a significant ($p < 0.05$) effect on Proso millet yield and reported that mechanical land preparation increased the yield by a factor of 2.41, compared to the manual land preparation.

In demographic factors, the tested variables had a positive effect on Proso millet yield except for gender, but none of them had a significant ($p > 0.05$) impact on the grain yield. Gender did not have an observable effect on the yield ($p = 0.69$) because of the very small sample size of the females (Table 2.3). However, according to the results, Proso millet yield increased by a factor of 0.87 with a male farmer and decreased by the same amount of factor for a female farmer. Both age and education level had a positive effect on the grain yield showing that increment of one age category and education level would result an increment of yield by a factor of 0.49 a and 0.85 respectively.

Proso millet is cultivated on a small scale (Figure 2.6) and the increment of one unit of land increased the yield by a factor of 2.71. In seed source, the yield increased by a factor of 0.79 when farmers used purchased seeds while the use of their own seeds decreased the yield by the same factor. Change of soil colour from dark to light colour decreased the yield by a factor of 0.46. As highlighted in section 2.4.3, weeds are a big issue and 50% of farmers used herbicide to control weeds. The use of herbicides increased the yield by a factor of 0.61 compared to the fields that were not treated with herbicides.

Attitudes of farmers and Proso millet yield

The relationship between Proso millet yield and the attitudes of farmers were evaluated using the nonparametric Spearman correlation. Out of the 10 attitudinal statements (Table 2.4), 4 had significant relationships with the yield at 90% probability level. These statements were; the cultivation is profitable ($p=0.06$), the crop needs a low level of water ($p=0.02$), it has fewer pests ($p=0.05$) and can tolerate climate change ($p=0.05$). Since the attitudes on benefits and opportunities of the cultivation had a positive impact on the yield, it is important to increase good attitudes towards Proso millet cultivation in the study area. Similarly, farmers whose yields have not been affected by pests experienced a positive impact on yield and believe that the crop has fewer pests. Therefore, yields also drive the attitudes among Proso millet farmers.

2.5. Discussion

In this study, the present situation of Proso millet cultivation in the growing region of LCZD Sri Lanka was studied using field sample collection, field observation and survey approaches. Malkanthi (2016) studied the underutilised crops in Moneragala district and found that out of 31 crops, Proso millet ranked top as the most cultivated

underutilised crop (along with finger millet) in the region (88.3% of 120 farmers). This popularity can be attributed with the unique characteristics of Proso millet that were found in “reasons to cultivate” in this study. Even though popular among farmers, low land availability which also revealed from the current study is one of the main problems of farming underutilised crops in the country (Malkanthi 2016). Since the reduction of the field size reduces Proso millet yield (section 2.4.7), it is important to increase Proso millet field size through proper extension programs.

According to the data collected from HARTI, Proso millet production has been declining over the last 2–3 decades. Discussion with farmers, merchants and people in the area confirmed that Proso millet production has been reduced in the last few decades. With the discussions, it was found that the main reasons for yield reduction are an abandonment of the crop for the introduction of cash crops like maize by private companies and benefits farmers get from them such as low cost/free seeds and fertiliser, free inspection and direct market. Since Proso millet is a neglected crop cultivated in a specific part of the country, still it did not receive much attention from the DOASL. Therefore, the available data on Proso millet production is not 100% reliable. The farmers in the study area involve in Proso millet farming for several generations. Therefore, they have their own knowledge received from their own experience, parents or ancestors on rituals and traditional crop management practices and adaptation techniques, that were revealed from the discussion with farmers. It is also important to protect this undocumented knowledge that is draining from the recent generations.

Soil samples were collected and analysed to study the properties of the soil on which Proso millet is cultivated. Proso millet farmers follow different land preparation techniques to loosen the soil as ploughing by tractor, mamoty or sow seeds without ploughing, therefore, bulk density values were different among the fields. Farmers do

not deep plough Proso millet fields to loosen the soil. Since Proso millet contains very shallow and fibrous root system (Baltensperger 1996), they can be grown easily in these fields. The soil pH in most of the fields belonged to the optimum range (5.5 to 6.5) for seed germination (Baltensperger 1996; Lyon et al. 2008) and growing (Krishna 2013). Since pH did not exceed 7.8, the chance to occur iron chlorosis is low (Habiyaemye et al. 2017) in Proso millet fields in the study region. Most of the farmers do not apply nitrogen into their Proso millet fields (section 2.4.2), therefore, nitrogen in the soil is low. However, farmers practice crop rotation in Proso millet fields that are in their backyards. Cultivation of groundnut, a legume as a rotating crop, fix nitrogen in the soil that increases soil nitrogen. Further analysis of macro and micro nutrients in the Proso millet growing soils are important to study more relationships between soil and the yield.

None of the observed Proso millet fields on which the harvest was collected ($n = 41$) in Moneragala and Hambanthota districts reported the maximum potential yield of 4 t ha^{-1} (DOASL). In general, the potential productivity of millets were $0.5\text{--}2.8 \text{ t ha}^{-1}$ (Reddy et al. 2003). Proper fertilising can maximise Proso millet forage yield to $6\text{--}10 \text{ t ha}^{-1}$ and grain yield to $1.2\text{--}8 \text{ t ha}^{-1}$ (Krishna 2013). Actions in terms of varieties, soil and crop management practices are essential to maximise the Proso millet yield in LCZD of Sri Lanka. No proper varieties were found from farm fields and it is important to introduce high yielding Proso millet varieties to subsistence farmers in LCZD Sri Lanka.

It was found that Proso millet farmers use high seed rates that leads to high plant densities. Farmers practice this as a weed management technique because Proso millet is a poor competitor with weeds by its nature. But, it was found that the very high plant density negatively affected the yield components. Agdag et al. (2001) analysed the effect of row spacing on grain yield and other agronomic characters of Proso millet

using different row spacing ranged from 15 to 46 cm and found that the increment of each centimetre in a row decreased the grain yield by 14 kg ha⁻¹ and stray yield by 160 kg ha⁻¹. Further, wider row spacing decreased the number of tillers per unit area and increased plant height by 0.17 cm per each cm increase in row width as a reason of interplant competition (Agdag et al. 2001). In yield components, the weight of Proso millet seed is one of the most stable parameters even with the moisture stress (Seghatoleslami et al. 2008). It was found that the weight of seeds did not have a clear relationship with plant density suggesting it is even stable under plant density too.

Proso millet harvest collected from the study area were planted in different dates within a few weeks period (Chapter 3). Anderson (1994) documented that biomass, plant height, water use efficiency and yield of Proso millet were affected by sowing date. Therefore, along with different management practices, soil properties, quality of seeds and seed/plant densities, sowing date also affects the Proso millet yield variability in the growing regions in Sri Lanka.

The results of logistic regression show the impact of demographic and crop-related data on Proso millet yield. Increased yield with the increment of age may be associated with the knowledge and experience farmers gain through the cultivation practices. The positive effect of education on Proso millet production may be the reason of exposure to many agricultural choices which came from science and agricultural related subjects that also reported by Madegwa (2015) for finger millet cultivation in Kenya. According to the logit model, mechanical land preparation significantly ($p < 0.05$) increased the yield but 56% of farmers use manual land preparation. Mechanical land preparation facilitates root growth and soil aeration, that increase the yield. Therefore, farmers should be encouraged to use mechanical land preparation to increase the yield and it is a no-cost adaptation technique.

Mohajer et al. (2012) analysed the forage yield and quality traits among 3 Proso millet varieties and found that Proso millet gave the significantly higher amount of both fresh forage and dry matter yield than Foxtail millet (*Setaria italica*) and Sainfoin (*Onobrychis sativa*). Non-grain above ground biomass of Proso millets are not used in Sri Lanka and they are left in the field where they were threshed without any use. It is important to promote the biomass utilisation of Proso millet as well as the introduction of new technologies to harness biomass production. Since farmers agreed that lack of knowledge on processing and value addition as a constraint to Proso millet cultivation, it also needs to introduce value added products, processing technologies and marketing facilities to Proso millet farmers.

Proso millet is cultivated in the early *Yala* season on which farmers cannot cultivate other crops due to low rainfall and occurrence of dryer spells (Chapter 3). Farmers get extra income in the climatologically unfavourable period by cultivating Proso millet. Since the statistics showed a declining trend, it is essential to encourage farmers and popularise the crop through educational and training programs, facilitating subsidies, marketing facilities and technical support (Malkanthi 2016). It is also good to increase the awareness on beneficial properties of Proso millet such as nutrient content and drought tolerance among the communities and introduction of advanced technologies, moisture conservation methods and post-harvest techniques for Proso millet cultivation in LCDZ Sri Lanka.

2.6. Conclusions

Proso millet, an underutilised minor millet, is cultivated in southern parts of Low Country Dry Zone Sri Lanka. Farmers follow a traditional farming system and Proso millet is found in *Chena* (shifting cultivation) with low inputs as a rainfed crop. Survey

results revealed that farmers cultivate Proso millet because of the high income generated and easy cultivation practices. Different land preparation techniques, quality of seeds, seed rates, and high variation of plant density created uneven Proso millet fields. Farmers maintain a very high plant density as an adaptation technique to protect against the rainfall and animal related damage to the crop and to control weeds. However, the increment of plant density affected the yield components of Proso millet as it significantly decreased panicles per plant, seed number per panicle and grain yield per plant. The yields reported by farmers are far below the potential value. When the attitudes of Proso millet farmers are taken into consideration, attitudes towards profitability, low level of water requirement, fewer pests and tolerate climate change had significant positive relationships with the yield. Therefore, it is also important to increase good attitudes towards Proso millet cultivation in the study area.

Rainwater harvesting, improvement of soil water and nutrient hold capacity and soil conservation was not practised in Proso millet fields. Therefore, research attention is required on seed/plant densities, soil improvement and management practices that increase the yield. Modern agricultural technologies should be introduced to low input agricultural systems in the region.

2.7. Chapter summary

- Proso millet is an under researched minor millet cultivated in drier parts of Sri Lanka and available literature suggests its suitability in unfavourable climatic conditions where other crops fail or give poor yields.
- Farmers in Sri Lanka cultivate Proso millet in low input subsistence farming systems as a rainfed crop.
- A good record on past data was not available for Proso millet suggesting its negligence in the country.
- The present situation, strengths, constraints and attitudes towards Proso millet cultivation were studied from the farmers' perspective.
- High spatial variability was observed among Proso millet fields due to different land preparation techniques, quality of seeds, seed rates and plant densities.
- The Proso millet yields reported by farmers are far below the expected potential yields.
- The results of on-farm field survey and harvest collection from farmer fields documented in Chapter 2 were used in model validation (Chapter 4).

Chapter 3

Climate characteristics of Proso millet growing regions in Sri Lanka*

3.1. Introduction

Despite the ongoing improvements in technology and crop types, food production remains highly dependent on climate inputs such as growing season temperatures and rainfall (Rosenzweig et al. 2001; Karunaratne and Wheler 2015). In tropical countries where temperature variations tend to be small, including in Sri Lanka, variations in rainfall are most important (Kurukulasuriya and Ajwad 2007; Esham and Garforth 2013). Indeed, rainfall in many parts of Sri Lanka is a key input to rainfed agriculture (Esham and Garforth 2013) and the production of cereals including rice, maize and millets (Punyawardena 2008).

Low amount of rainfall is one of the main limiting factors for crop production (Seghatoleslami et al. 2008) and identified as a challenge to agriculture in many developing countries (Ceccarelli and Grando 1996). Cultivating drought tolerant crops rather than water demanding crops is an efficient strategy for crop production in dry areas (Seghatoleslami et al. 2008). Proso millet is believed to have drought tolerant characteristics, therefore it is identified as an alternative drought tolerant crop that is suitable for water scarce environments (Chapter 2). It is important that these hardy

* *The chapter based on the manuscript (accepted):* Wimalasiri GEM, Ashfold MJ, Walker S, Nissanka SP, Karunaratne AS. 2017. The Relationship Between Rainfall Characteristics and Proso Millet (*Panicum miliaceum* L.) Cultivation in Low Country Dry Zone, Sri Lanka. Tropical Agricultural Research and Extension. 20(1 & 2):32-44 *and conference paper:* Wimalasiri GEM, Ashfold MJ, Walker S, Karunaratne AS. 2016. Rainfall trends over Proso millet growing regions in Sri Lanka. 3rd International Conference of Agricultural Science, Sabaragamuwa University of Sri Lanka; December 8–9; Belihuloya, Sri Lanka. p. 57–59.

crops receive research attention because resilient agriculture is a good strategy to overcome the increased risk of droughts and monsoon-related interannual rainfall variability in the Asian region (IPCC 2014).

Gunarathna et al. (2004) claimed that in line with the changes of rainfall pattern in Hambanthota district in the Low Country Dry Zone (LCDZ) with respect to the magnitude of mean monthly and annual rainfall, the risk of dry spells, onset and the cropping calendar also changed. Further, changes in rainfall pattern create water shortage periods during cropping seasons that badly affect crop yield. This example illustrates the importance of adjusting the cropping calendar to suit the current rainfall pattern in the Dry Zone (DZ) of Sri Lanka (Gunarathna et al. 2004).

The date of onset of the rainy season is one of the most critical factors in the agricultural calendar (Omotosho et al. 2000; Ingram et al. 2002; Barbier et al. 2009; Guenang and Kamga 2012). Knowledge of the probable date of onset, as well as the date of retreat of the rainy season and the duration of dry spells is very useful for farmers in planning various agronomic practices such as land preparation, seed/plant arrangement, sowing, labour and machinery, harvesting, threshing and drying (Omotosho et al. 2000; Mavi and Tupper 2004; Avila et al. 2013). Late onset or early ending of the growing season significantly affects the crop yield (Mugalavai et al. 2008). Each crop has its own critical periods during its growing season. Farmers can adjust sowing periods in a way that moisture sensitive stages are less likely to fall during dry spells based on the knowledge on the frequency of occurrence of wet and dry spells during growing period (Mavi and Tupper 2004). Sri Lankan farmers use several empirical techniques, such as the sighting of the migrant Grey Wagtail bird to anticipate the rain (Zubair 2002). Identification of sowing and onset/retreat days and existing strategies on crop selection

and crop management will be helpful in agricultural decision making in the future under a changing climate.

Very limited research attention has been devoted to assessing the links between agro-climatic characteristics and cultivation of Proso millet in Sri Lanka. With the link to the present situation of Proso millet cultivation (Chapter 2), the objectives of Chapter 3 is to explore the characteristics of rainfall, onset, retreat and length of the season, trends of long-term dry spells and farmers' crop husbandry strategies on Proso millet farming systems in Low Country Dry Zone in Sri Lanka. The chapter describes the summary of the climate characteristics where Proso millet accessions for crop modelling work (Chapter 4) were collected.

Chapter 3 is structured as follows: an overview of the literature on climate and crop production in Sri Lanka is presented in section 3.2 followed by the description of the study area, the data used and methodology in section 3.3, results in 3.4 and the discussion in section 3.5. Section 3.6 concludes Chapter 3.

3.2. Climate and crop production in Sri Lanka

Sri Lanka is a tropical island (between 5° and 10° N latitude) in the Indian Ocean with the year-round warm weather. Being close to the equator, rainfall is the key climatic parameter for crop production in the country (Punyawardena and Kulasiri 1996). But it is highly unpredictable with irregular distribution (Punyawardena and Kulasiri 1996; Sonnadara 2015). The daily mean temperature of the country ranges from 16 °C in central highlands to a maximum of 33 °C in low altitudinal coastal areas (Sonnadara 2015). Marked seasonal temperature variation cannot be observed in Sri Lanka.

There are three major climatic zones in Sri Lanka defined according to annual rainfall amount: the Wet Zone (annual rainfall >2500 mm) in the central and southwestern

region, the Dry Zone (<1750 mm rain annually) covering the south-east, east and northern parts of the country, and the Intermediate Zone (annual rainfall 1750–2500 mm) separating the two (Figure 3.1A). Further, the diversity in temperature, rainfall and other physical environmental factors has led to the definition of 46 agroecological zones (AEZ) where different crops or crop combinations are cultivated (Punyawardena 2008). The Proso millet growing region considered in this thesis belongs to two AEZs; namely DL_{1a} (Low Country Dry Zone region 1–a, a region in the south of Sri Lanka characterised by 1100–1750 mm/year rainfall) and DL_{1b} (Low Country Dry Zone region 1–b characterised by 900–1750 mm/year rainfall). More than 90% of this area experience severe drought during the minor growing season named “*Yala*” (Chithranayana and Punyawardena 2008) that will be described later in this section.

Around 70% of the total annual rainfall of the country occurs during a shorter rainy season during October to January period due to the convectional activity and monsoonal circulation (Punyawardena and Kulasiri 1996). Further, the regular formation of cyclonic depressions in the Bay of Bengal (November and December) and minor convective rainfall (late March to mid-May) also brings rainfall to Sri Lanka (Punyawardena and Kulasiri 1996). Annual rainfall of the country is highly variable; ranges from causing droughts due to lack of rainfall that lasts for months, periods of extreme precipitations, storms and floods (Manawadu and Fernando 2008). Agricultural patterns across the country are related to monsoon rains at a particular time of the year: First Inter-Monsoon (FIM) from March to May, South West Monsoon (SWM) from June to September, Second Inter-Monsoon (SIM) from October to November and North East Monsoon (NEM) from December to February (Suppiah 1996). As a result of these monsoons, rainfall in Sri Lanka typically follows a distinctly bimodal pattern, leading to two cropping seasons. Especially in the Dry Zone, the

principal or the major cultivation season (*Maha* – wet season) starts with SIM from October and lasts until February, and the subsidiary cultivation season or the minor growing season (*Yala* – low rainy season) constitutes six months from March to September (De Silva et al. 2007). Therefore, any changes in monsoonal rainfall can damage crop husbandry in Sri Lanka. Even though the onset of *Yala* and *Maha* seasons are traditionally assigned to different months of the year, the actual start, end and length of the season can vary with the onset and cessation of rainfall in an area. In general, the duration of the *Yala* season was defined inconsistently by different authors as March to August (Chithranayana and Punyawardena 2008), March to September (De Silva et al. 2007), March to October (Wickramagamage 2015), April to August (Sonnadara 2015), April to September (Zubair 2002), May to August (Seo et al. 2005) and May to September (Droogers 2004). Therefore, it is essential to identify the actual onset and retreat to assist agricultural planning in a particular area of study.

Since the agriculture plays an important role in the economy (6.9% GDP – Central Bank Sri Lanka 2017) and the lifestyle of people in Sri Lanka (Punyawardena and Kulasiri 1996), it is important to understand the temporal variation in climate, especially the intra-monsoonal variation that causes wet and dry spells, to improve the agricultural productivity in the country (Sonnadara 2015).

The available literature on climate and crop cultivation in Sri Lanka was summarised in section 3.2. Since the relationship between agro-climatic characteristics and cultivation of underutilised crops like Proso millet received less research attention, following methodologies were used study the growing seasonal characteristics in cultivating areas in Sri Lanka and their impact on Proso millet cultivation.

3.3. Methodology

3.3.1. Site description and data

Proso millet growing region (Chapter 2) that belongs to LCDZ region 1a (DL_{1a} – a region characterised by 1100–1750 mm/year rainfall) and LCDZ region 1b (DL_{1b} – area with 900–1750 mm/year rainfall) was selected for the study (Figure 3.1A).

Climate data

Station data

Historical daily rainfall data were collected from five meteorological stations located in the Proso millet growing region (Figure 3.1B). Data from Pelwatta (6.72°N, 81.20°E, covering 1983–2015) and Sewanagala (6.40°N, 80.91°E, 1986–2015) were collected from Lanka Sugar Company Ltd., Udawalawa (6.41°N, 80.84°E, for 1993–2015) from Sugarcane Research Institute Sri Lanka and Thanamalwila (6.44°N, 81.13°E, 1989–2015) and Kuda Oya (6.62°N, 81.23°E, 1989–2015) from stations governed by the Department of Irrigation Sri Lanka (Table 3.1). Missing data were omitted in the analysis.

Table 3.1. Geographical distribution and rainfall dataset of five meteorological stations used in the study

Station	Latitude (°N)	Longitude (°E)	Data period	Missing data %	Agroecological zone
Pelwatta	6.72	81.20	Jan 1983 – Dec 2015	–	DL _{1a}
Udawalawa	6.41	80.84	Jan 1993 – Jul 2015	–	DL _{1a}
Sewanagala	6.40	80.91	Jul 1986 – Jul 2015	2.57	DL _{1b}
Thanamalwila	6.44	81.13	Oct 1989 – Nov 2015	3.84	DL _{1b}
Kuda Oya	6.62	81.23	Oct 1989 – Nov 2015	1.90	DL _{1b}

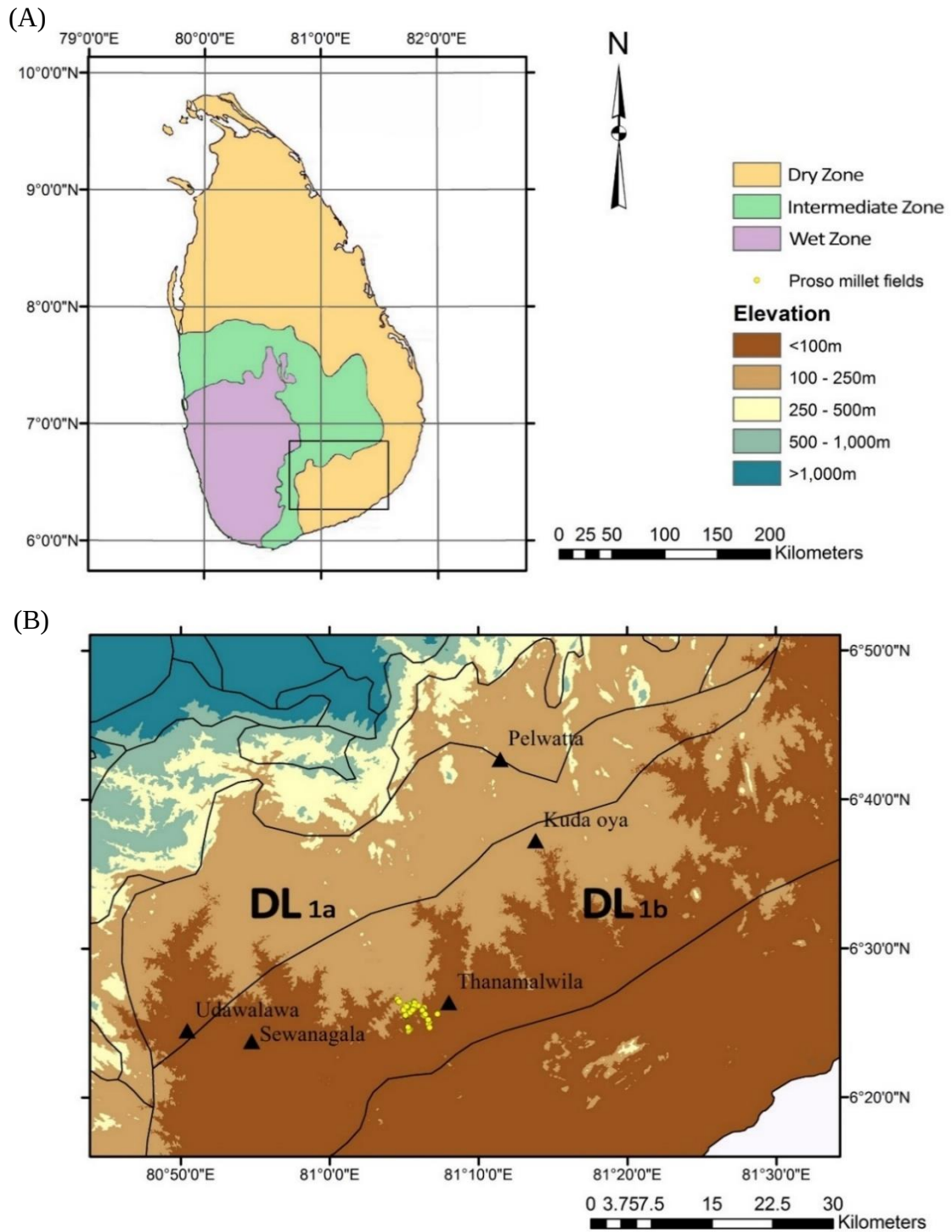


Figure 3.1. (A) Major climatic regions and location of the Proso millet growing area (black square) within Sri Lanka and (B) the distribution of meteorological stations (black triangles) and farmer's fields (yellow circles – Figure 2.2 in Chapter 2) used in the study. The DL_{1a} and DL_{1b} AEZs are also marked. Black lines are the boundaries between AEZs.

Reanalyses data

Rainfall in DZ Sri Lanka is erratic (Sonnadara 2015) and localised. For this reason, to obtain data during the study period for the area where Proso millet is cultivated, NASA Prediction of Worldwide Energy Resource (POWER; Zhang et al. 2007) dataset (<https://power.larc.nasa.gov/>) derived from the Goddard Earth Observing System assimilation model and available on a 1-degree grid was used.

3.3.2. On-farm field survey

The data on the dates of sowing and harvesting, crop management practices and selection of crops were collected from the on-farm field survey that was described in Chapter 2.

3.3.3. Definitions for a wet day, onset, retreat and length of the growing season

The onset of the growing season is the first day when the rainfall amount equals or exceeds a defined threshold value (Aviad et al. 2004). Following Stern et al. (2003), the threshold value of 0.85 mm in the Instat statistical programme was used to define a wet day. Therefore, a day with more than 0.85 mm rainfall was a wet day while a day with less than 0.85 mm of precipitation was considered as a dry day.

A number of definitions of the onset and retreat of the growing season exist in the literature depending on the geographical location and the timescale used (Punyawardena 2002; Gunarathna et al. 2004; Sonnadara 2015). A criterion for onset and retreat that is favourable for Proso millet growing region in Sri Lanka was selected. Rainfall in the DZ of Sri Lanka is irregular, therefore, it is important to evaluate rainfall for a few consecutive weeks to avoid falsely identifying the onset (Punyawardena 2002; Sonnadara 2015). Marteau et al. (2011) reported that dry spells lasting at least 7 days after a 2-day wet spell caused failures of Pearl millet, a similar crop to Proso millet,

sown in Southwest Niger. False start of a season was avoided by not allowing a dry spell of more than 10 days after the start of the growing season (Mupangwa et al. 2011). Therefore, the onset of the season was defined as the first occasion with more than 20 mm rainfall in a 1 or 2 days period after 1st March with no dry spell of 10 days or more within the following 30 days period. Any onset after 1st May was considered as a very late onset event. The retreat of the season was defined as the first occurrence of a dry spell of three consecutive weeks with less than 20 mm of rainfall after 1st May, as adopted by Punyawadena (2002) for the DZ of Sri Lanka. The period between onset and retreat was considered as the length of the growing season. Meteorological definitions used in the study are summarised in Table 3.2.

Table 3.2. Summary of the metrological definitions used in the study

Event	Definition
Wet day	A day with more than 0.85 mm rainfall
Dry day	A day with less than 0.85 mm of rainfall
Onset of the season	The first occasion with more than 20 mm rainfall in a 1 or 2 days period after 1 st March and no dry spell of 10 days or more within the following 30 days period
Retreat of the season	The first occurrence of a dry spell of three consecutive weeks after 1 st May, with less than 20 mm of rainfall
Very late onset	Any onset after 1 st May
Length of the season	The period between onset and retreat

3.3.4. Trends of annual, growing seasonal and monthly rainfall amount

The monotonic trends in precipitation were detected using the Mann-Kendall statistical test. The Mann-Kendall test is a non-parametric analysis introduced by Mann (1945) and developed by Kendall (1975). It has been widely used in rainfall analysis, hydrology and environmental sciences.

The Mann- Kendall test statistic is given as follows

$$Z_{mk} = \begin{cases} \frac{S - 1}{\sqrt{var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S + 1}{\sqrt{var(S)}} & S < 0 \end{cases}$$

in which,

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^n sgn(x_k - x_i)$$

$$var(S) = \frac{n(n-1)(2n+5) - \sum_i e_i(e_i-1)(2e+5)}{18}$$

Where Z_{mk} , is the Mann-Kendall statistics, x_k, x_i are the sequential data values and n is the length of the dataset. The extent of any given tie is e_i and $\sum$ stands for summation over all ties. A positive value of Z_{mk} indicates an increasing trend, i.e., value increase with time and a negative value indicates a decreasing trend, i.e., value decrease with time (Ampitiyawatta and Guo 2009).

3.3.5. Long-term trends of onset and retreat days

Nonparametric Mann-Kendall trend analysis (Mann 1945; Kendall 1975) was performed to detect the long-term variations in onset and retreat dates. Retreat dates for very late onset were omitted in the analysis because the *Yala* season was considered to have failed in those years and onset dates would belong to *Maha* (major) season.

3.3.6. Dry spell analysis

Daily rainfall data were used to evaluate the trends in dry spells in Proso millet growing region in Sri Lanka. For the precise estimation of the direct method of climate data analysis, at least 30 years of climate data are necessary (Stern et al. 2003), therefore an alternative approach was used. The daily rainfall data were fitted according to zero-order Markov chain model. It was assumed that the amount of daily rainfall follows an exponential distribution (Stern et al. 2003). Dry spells that last more than 7 days are linked with re-sowing of Pearl millet in Niger due to death of germinated plants (Marteau et al. 2011) and can adversely affect the final yield. Therefore, the probability of 7-day dry spells over the period of 30 days centred on a particular day was plotted by the Markov chain model for the Proso millet growing season.

3.3.7. Data analysis

Dry spells were analysed using Instat Statistical Programme (Version 3.036) (Stern et al. 2003). The relationship between onset and length of the season and, onset and seasonal rainfall at each meteorological station were determined using regression analysis. The significance of the deviation of the regression slope from zero was checked. The F-test, t-test and regression analysis were conducted using Prism (Version 7.03).

3.4. Results

3.4.1. Rainfall distribution and crop cultivation pattern in the area

Distribution of rainfall in Proso millet growing area, that belongs to Low Country Dry Zone in Sri Lanka, showed a bimodal variation with two peak rainy periods centred on April and November (Figure 3.2A). The first peak belongs to *Yala* season and the second to *Maha* season. Farmers cultivate Proso millet during the initial phase of *Yala* season where farmers get the highest rainfall amount.

The on-farm field survey (Chapter 2) yielded important information on the selection of crops and management practices based on rainfall distribution (Figure 3.2B). Proso millet farmers start to clear lands from mid January – February and finish by mid March. The crop is extensively found in *Chena* systems and farmers clear scrub jungles/fallow vegetation and burns it to begin cultivation. They start Proso millet cultivation generally after 15th March, with the commencement of rain from FIM and harvest 60–70 days after sowing, i.e. in late May – early June period. Harvesting is done by removing the individual heads with sickles or small hand knives. Then it is threshed and sun-dried up to two weeks. Since June – July is a drier period in the region (Figure 3.2A), farmers harvest, thresh and sundry Proso millet seeds without being affected by rain. Farmers in the area are not involved in agricultural practices during August because it is dry and very hot during that part of the year. They start land preparation for Other Field Crops (OFC) such as finger millet (*Eleusine coracana*), foxtail millet (*Setaria italic*), sesame (*Sesamum indicum*), mungbean (*Vigna radiata*) and groundnut (*Arachis hypogaea*) during September, the last month in *Yala* season. Some farmers cultivate these crops in their backyards while others in cleared lands that have been used for Proso millet cultivation. The lifespan of these crops are longer than Proso

millet and they require more water (Department of Agriculture Sri Lanka). High rainfall from SIM and NEM during *Maha* season fulfils the water requirement of these crops. Most of the farmers also do paddy cultivation during that period because they receive enough rainfall and the OFC do not require much attention. Both rice and OFC are harvested in mid-December – January. Again, Proso millet farmers start land preparation in the following year for *Yala* season in a different location or same field and this cycle continues. It was clearly observed that the pattern of agriculture in Proso millet growing region is directly linked to the distribution of rainfall (Figure 3.2B).



Figure 3.2. (A) Distribution of mean monthly rainfall during the 1983–2015 period and (B) farming activities during the year in Proso millet growing region of Sri Lanka. In (A) the standard error of the mean (SEM) is used in error bars.

3.4.2. Rainfall amount

The mean annual rainfall of the Proso millet growing region, that was calculated using five meteorological stations, was 1399 ± 194 mm for the study period (1983–2015) while for stations in DL_{1a} and DL_{1b} AEZs it was 1578 ± 63 mm and 1280 ± 140 mm respectively. The lower limits of mean annual rainfall for definitions of DL_{1a} and DL_{1b} AEZs are 1100 mm and 900 mm respectively, and the upper limit of DZ is 1750 mm (Punyawardena, 2008). The annual rainfall during the 1983–2015 period was below the upper limit, confirming that all the stations studied belong to the DZ (Table 3.3).

Table 3.3. Mean annual and Proso millet growing seasonal (15th March–15th June) rainfall of the Proso millet growing region during 1983–2015 period with standard deviation. AEZs are mentioned in parenthesis.

Station	Total annual rainfall (mm)	Proso millet growing seasonal rainfall (mm)	Years with Proso millet growing seasonal rainfall amount lesser than the threshold*	Rainy days within a growing season (%)
Pelwatta (DL _{1a})	1623 ± 314	374 ± 140	33%	$47 \pm 11\%$
Udawalawa (DL _{1a})	1534 ± 246	437 ± 85	9%	$45 \pm 10\%$
Sewanagala (DL _{1b})	1439 ± 295	397 ± 96	14%	$47 \pm 10\%$
Thanamalwila (DL _{1b})	1226 ± 370	302 ± 122	54%	$46 \pm 15\%$
Kuda Oya (DL _{1b})	1175 ± 328	293 ± 123	75%	$42 \pm 10\%$

*300 mm (Changmei and Dorothy 2014)

The mean amount of rainfall during the Proso millet growing season (361 ± 62 mm) is higher than the lower limit (300 mm) where Proso millet gives a satisfactory yield, according to the literature (Changmei and Dorothy 2014). Out of all, a mean of 36.4% Proso millet growing seasons in the region received less than the lower limit while the highest incidences were from the driest parts, as Kuda Oya 75% and Thanamalwila 54%, suggesting rainfall amount is a limiting factor for Proso millet cultivation in these areas.

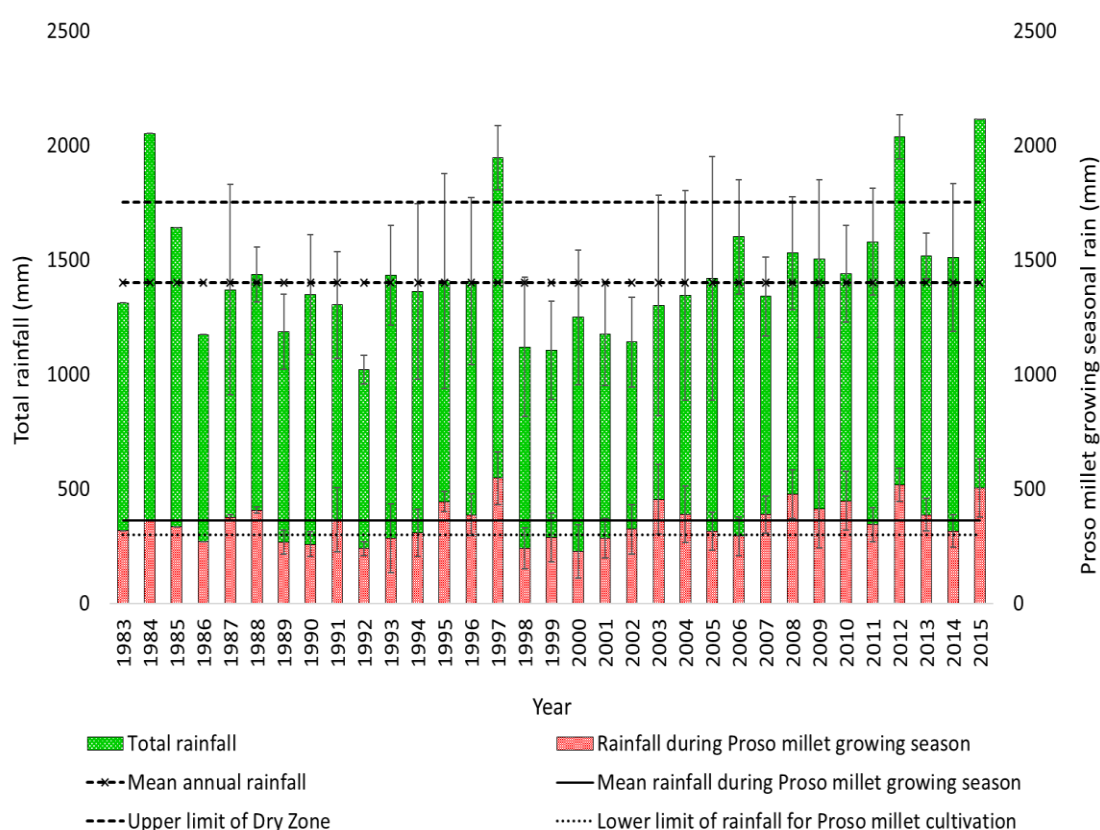


Figure 3.3. Interannual variability of rainfall, averaged over the 5 sites, in the Proso millet growing region of Sri Lanka (1983–2015). Error bars present the standard deviation of respective means. Mean annual rainfall (above) and mean rainfall during Proso millet growing season (below) are marked in vertical lines while dash (above) and dot (below) lines represent the upper limit of Dry Zone (Punyawardena 2008) and lower limit of rainfall for Proso millet cultivation (Changmei and Dorothy 2014).

Nearly half of the days of the growing season (42% in Kuda Oya to 47% in Pelwatta and Sewanagala) were rainy days in the Proso millet growing region. The study area received more rainfall than the mean annual rainfall during the last 7 years (2008–2014) prior to the on-farm field survey (Figure 3.3). From discussion with farmers, it was found that farming communities were able to recall these recent experiences and use as evidence in agricultural decision making. The relationship between annual rainfall and the percentage of rainfall during Proso millet growing season was weak ($R^2 = 0.0147$) across the region.

3.4.3. Rainfall trends in the study area

In general, the total annual rainfall in Proso millet growing region showed an increasing trend (Table 3.4). Kuda Oya showed the highest increasing trend followed by Pelwatta and Sewanagala. The FIM brings more rainfall to Dry Zone during *Yala* season. All the stations showed a positive trend for FIM but the trend was significantly ($p < 0.05$) increasing in Thanamalwila and Kuda Oya only. These two stations are the most arid stations among others and experienced long-term dry spells in most part of the year (section 3.4.7). The positive trend observed in Thanamalwila for SWM was not significant ($p > 0.05$). All other stations showed negative rainfall trends during SWM while only Udawalawa had the significantly ($p < 0.05$) decreasing trend. SIM and NEM monsoon showed an increasing trend in all the stations where Pelwatta showed significant ($p < 0.05$) trend for both rainy seasons followed by Sewanagala in SIM and Thanamalwila in NEM. Other stations did not show significantly ($p > 0.05$) increasing or decreasing trends.

Rainfall during *Yala* showed an increasing trend in four stations out of five but none of them was significant ($p > 0.05$). The negative rainfall trend for the *Yala* season in

Udawalawa also did not show a significant trend ($p > 0.05$). Even the total rainfall during *Yala* season is increasing, the negative trend in SWM suggests the risk of drought periods in the later part of *Yala* growing season in the study area. Rainfall during *Maha* season showed significantly ($p < 0.05$) increasing trend in Sewanagala, Pelwatta and Kuda Oya. But the positive trends in two other stations were not significantly ($p > 0.05$) increasing.

Mann-Kendall analysis of monthly rainfall showed that no significant ($p > 0.05$) trend was detected in any of the months in Udawalawa, Thanamalwila and Kuda Oya. The July rainfall decreased across the study area but significantly ($p < 0.05$) negative trend was recorded only in Sewanagala.

Table 3.4. Summary of Mann-Kendall trend analysis of rainy seasons in Proso millet growing area in Sri Lanka. AEZs are mentioned in parenthesis.

Season	Mann-Kendall Statistics				
	Pelwatta (DL _{1a})	Udawalawa (DL _{1a})	Sewanagala (DL _{1b})	Thanamalwila (DL _{1b})	Kuda Oya (DL _{1b})
Total	0.31*	0.2	0.27*	0.26	0.37*
FIM	0.09	0.08	0.14	0.31*	0.35*
SWM	-0.11	-0.32*	-0.15	0.05	-0.15
SIM	0.27*	0.29	0.30*	0.23	0.14
NEM	0.26*	0.01	0.12	0.33*	0.28
<i>Yala</i>	0.05	-0.1	0.13	0.29	0.11
<i>Maha</i>	0.27*	0.29	0.37*	0.07	0.32*

* denotes a significant trend ($p < 0.05$)

In contrast, November in both Sewanagala and Pelwatta showed positive trends along with April in the latter station. November rainfall increased in every station, but the trend was not significant ($p > 0.05$).

3.4.4. Onset, retreat and length of the growing season

No significant differences ($p > 0.05$) were observed in the time of the onset of the growing season between meteorological stations whereas significant differences ($p < 0.05$) were observed in retreat date of the season (Table 3.5). The mean onset and retreat across the region were 24th March (belongs to the 12th week starting from January) and 15th May (20th week) respectively (Figure 3.4). In general, wetter AEZ (DL_{1a}) recorded an early mean onset (20th March) and late mean retreat (17th May) than the drier AEZ (DL_{1b}) on which the onset and retreat dates were 26th March and 12th May respectively. The length of the season and the amount of seasonal rainfall showed significant differences ($p < 0.05$) between stations.

Mean length of the growing season in the Proso millet growing region was 52 ± 8 days (7.4 ± 1.1 weeks). During the study period, the rainy season averaged 58 days in DL_{1a} and 48 days in DL_{1b} AEZ. The length of the growing season decreased along the DL_{1a} to DL_{1b} AEZ (Table 3.5). Proso millet requires 60–70 days to reach maturity, therefore it will experience a dry period for 2–3 weeks before harvesting. Discussion with farmers during on-farm field survey (Chapter 2) revealed that Proso millet farmers prefer drier period at the latter stage of the crop because rainfall at this stage will cause seeds to shatter and plants to lodge. Higher rainfall during harvesting stage will interrupt the harvesting and postharvest handling practices, reducing both quantity and the quality of the Proso millet yield.

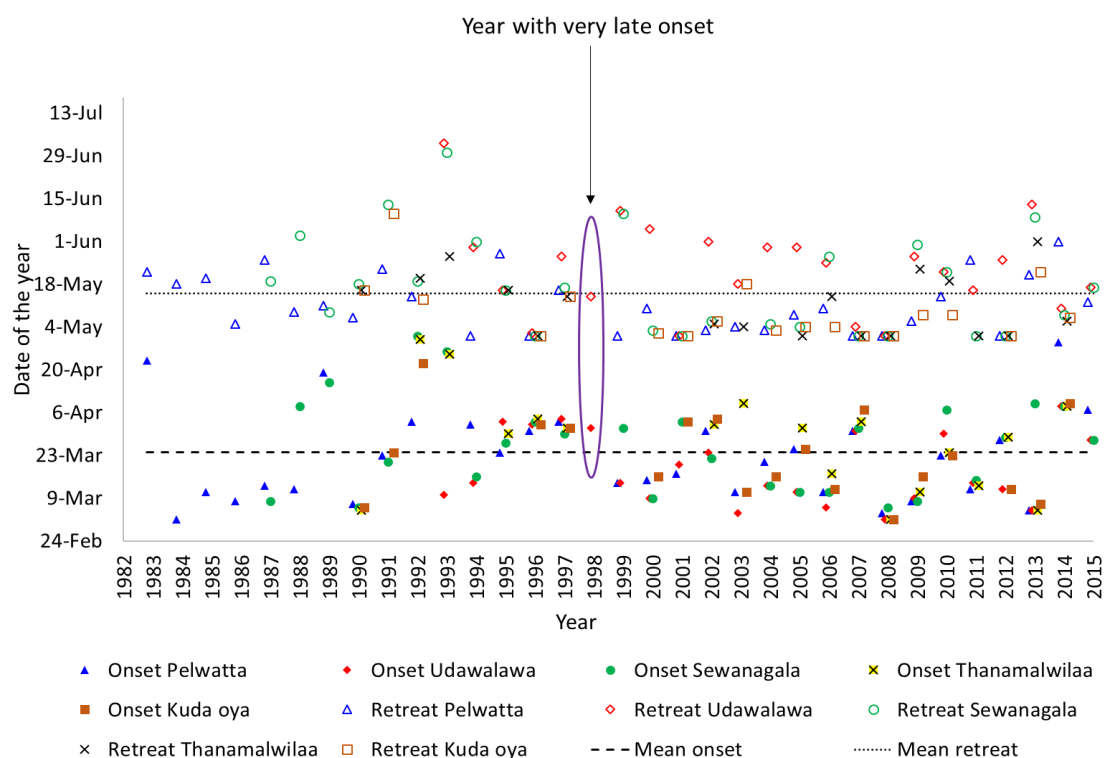


Figure 3.4. Onset and retreat dates for the *Yala* rainy season derived from daily rainfall data for the 1983–2015 period in Proso millet growing region of Sri Lanka. The dash (below) and dot (above) lines show mean onset (23rd March) and mean retreat (15th May) dates across the region. A year with a very late onset also marked.

Thanamalwila recorded the shortest mean length of the season (Table 3.5). This was further complicated by the fact that onset at Thanamalwila was more variable than retreat and the higher SD for both onset and season length (Table 3.5). Therefore, timely land preparation and seed broadcasting are more critical in Thanamalwila.

A mean of 9.4% of onset events was not identified within the *Yala* season across the study region because it did not occur within the defined time period (1st March – 1st May). In such cases, the years were identified as years with very late onset (Table 3.5). Each station except Udawalawa showed very late onset at least once and the highest number of these events were recorded from the driest part of the study region, namely Thanamalwila (20.83 %) and Kuda Oya (16.67 %) (Table 3.5). Proso millet farmers experienced a water shortage throughout the growing season in these stations

suggesting the cultivation was at risk. Except for Pelwatta, all other very late onset events belonged to *Maha* (the second growing season) in the region.

Mann-Kendall trend analysis revealed that there was no significant ($p > 0.05$) long-term increasing or decreasing trends in the onset and retreat dates and length of the season at four stations except Thanamalwila during the 1983–2015 period as onset showed a significantly decreasing trend at Thanamalwila ($p < 0.05$). Due to the observed increasing trend of growing season length at Thanamalwila and Kuda Oya, the stations with the shortest growing season length (45 and 47 days respectively) have a potential of supporting crop growth in the future in terms of length.

3.4.5. The relationship between sowing and harvesting dates with rainfall distribution

Returning to information obtained from the farmer survey (Chapter 2), reported sowing and harvesting frequencies during *Yala* 2015 are plotted along with daily rainfall amounts from Thanamalwila (the closest meteorological station – 6.5 km away from the centre of the survey area) and from POWER in Figure 3.5. The results of t-test revealed that rainfall amount of two datasets were not significantly different for 1st March – 30th June 2015 period ($p=0.5223$) while significantly different ($p < 0.0001$) for complete data set (POWER data available for January 1997 – October 2015 period) at 95% probability level. Based on Thanamalwila data, onset and retreat of the 2015 *Yala* season were 3rd April and 17th May respectively, while for POWER data, they were 27th March and 15th June respectively.

From the survey results, it was found that Proso millet fields were sown from 23rd March to 10th April 2015 while harvested from 23rd May to 5th June 2015 period. The mean and median sowing dates were 29th March (SD 4 days) and 28th March

respectively. The mean harvesting date was 1st June (SD 3 days) and the median was 31st May.

Before starting the cultivation, farmers ask about rainfall events from other farmers who have fields away from the survey area or who have visited other areas. Discussions with farmers revealed that some localised rainfalls helped farmers to start the Proso millet cultivation, but they were not recorded at Thanamalwila meteorological station (Figure 3.5). Further, a total of 82% of the fields in the survey area was sown on the date of onset at Thanamawila. Therefore, the observed daily rainfall data at Thanamalwila does not, in this case, appear suitable for describing the farmer survey area, hence, POWER data were used for further analysis in this section.

The first sowing event was recorded on 23rd March in the survey area. Not all the farmers waited until the onset or a rainy day to start planting the crop as 4 % sow Proso millet before the rains begin (on a dry day). Rest of the fields (96%) were sown after receiving 7 mm of rain. Among all, 22% of the fields were sown before the onset of the season (27th March). The highest percentage of sowing events (26%) was on the day following onset. Some farmers (12%) broadcast seeds one week after the onset. In such cases, farmers reported a failure to clear lands due to rain, lack of labour and family problems (such as funerals) led to the delay in sowing seeds.

Table 3.5. Median dates for onset and retreat, mean length of the season and the earliest and most delayed onset and retreat and events with very late onset in Proso millet growing region in Sri Lanka. AEZs are mentioned in parentheses.

Station	Median onset date	Standard deviation (days)	Earliest onset date	Most delayed onset date	Median retreat date	Standard deviation (days)	Earliest retreat date	Most delayed retreat date	Mean length of the season with SD (days)	Years with very late onset
Pelwatta (DL _{1a})	21–Mar	15	2–Mar	29–Apr	10–May	9	1–May	1–Jun	50±16	6.07 %
Udawalawa (DL _{1a})	14–Mar	12	2–Mar	8–Apr	25–May	15	1–May	3–Jul	66±23	0 %
Sewanagala (DL _{1b})	28–Mar	15	6–Mar	1–May	17–May	16	1–May	30–Jun	52±19	3.57 %
Thanamalwila (DL _{1b})	1–Apr	16	2–Mar	30–Apr	14–May	10	1–May	1–Jun	45±19	20.83 %
Kuda Oya (DL _{1b})	23–Mar	14	2–Mar	22–Apr	6–May	10	1–May	10–Jun	47±17	16.67

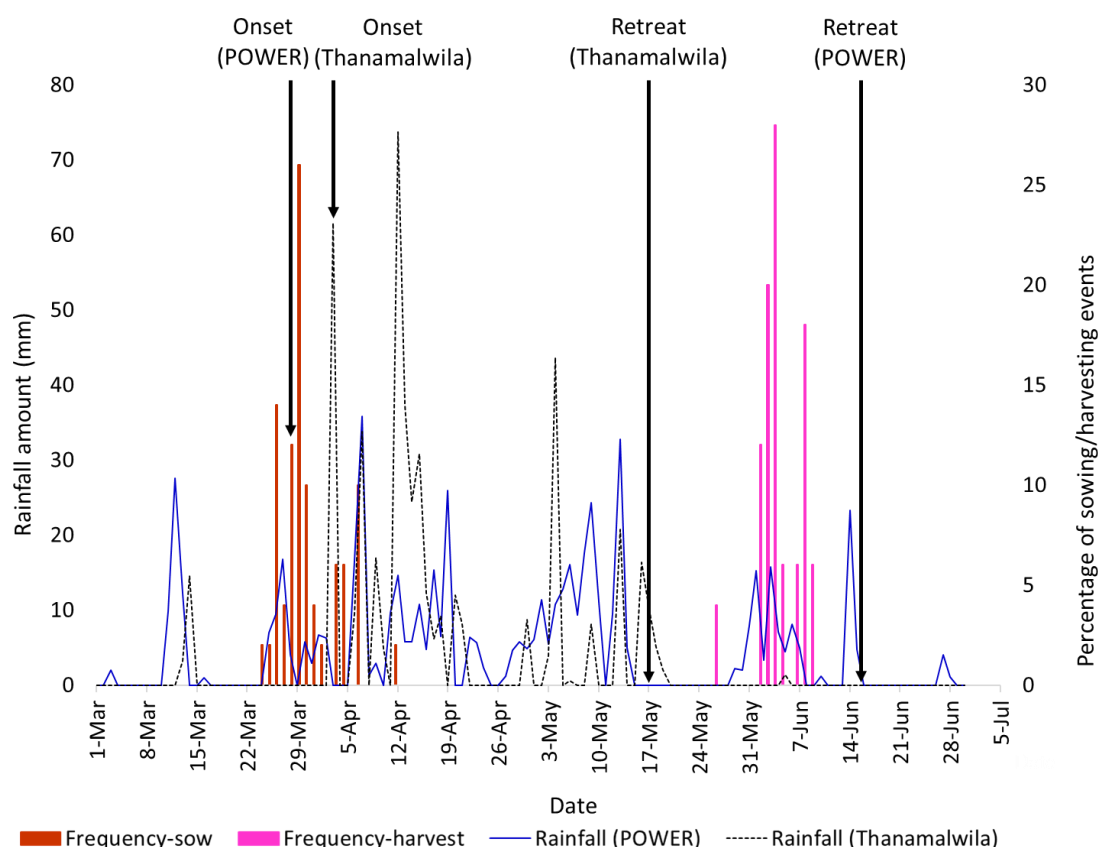


Figure 3.5. Farmers' sowing and harvesting dates of Proso millet and distribution of rainfall (POWER – straight blue line and Thanamalwila Observed – dot line) in Thanamalwila, Sri Lanka during 2015 *Yala* season

All the farmers harvested Proso millet during the rainy season (before the retreat day). The earliest harvesting (4%) was on 23rd May and the remaining fields were harvested within an 8-day period from 29th May. The length of the growing season (81 days) from POWER data for 2015 was longer than the mean length of 52 days across the region throughout the study period (1983–2015). Further, it was higher than the length of the season averaged across the 5 sites (45 days) for the year 2015. The length of the growing season at Thanamalwila in 2015 was 44 days.

Drier conditions during harvesting period are favourable for proper harvesting and post-harvest handling as described earlier. Results of the on-farm field survey revealed that labour availability is a big issue in the area, especially for harvesting (Chapter 2). Due

to lack of labour, harvesting of Proso millet can be delayed by several days. In 2015, the harvest was damaged due to unexpected rain, but 64% of farmers harvested their fields before receiving 10 mm of rain, half of the amount for the onset. In such cases, farmers delayed threshing and kept the harvest in the field as a heap covered using a polyethene to protect the grain. It was often observed that some matured fields or parts of them were left without harvesting due to rain and weeds.

3.4.6. Relationships of growing seasonal characteristics

Available evidence seems to suggest that there was a considerably higher correlation ($r = -0.7335$, significant at $p < 0.05$) between the onset and the length of the growing season than other relationships across Proso millet growing region in Sri Lanka (Figure 3.6A) as the relationship was significant ($p < 0.05$) in all five stations.

A stronger relationship between onset and length of the rainy season was observed at Thanamalwila ($r = -0.851$) compared to four other stations. The steepest gradient of the relationship at Udawalawa indicated that a delayed start has a more negative impact on the length of the season. In most cases (65.8%), the length of the season is shorter than the Proso millet lifespan (60 days) indicating that the crop experienced drought condition during reproductive and maturity stages (Figure 3.6A). The highest and the lowest percentage of events that the growing season length was lower than the Proso millet lifespan were recorded from Thanamalwila (78.9%) and Udawalawa (39.1%) stations respectively. The length of Udawalawa and Sewenagala *Yala* season exceeded 75 days on several occasions (47.8% and 14.8% respectively) when harvesting and postharvest handling of Proso millet could be affected by rainfall as happened during 2015 at Thanamalwila, Sri Lanka (Figure 3.5).

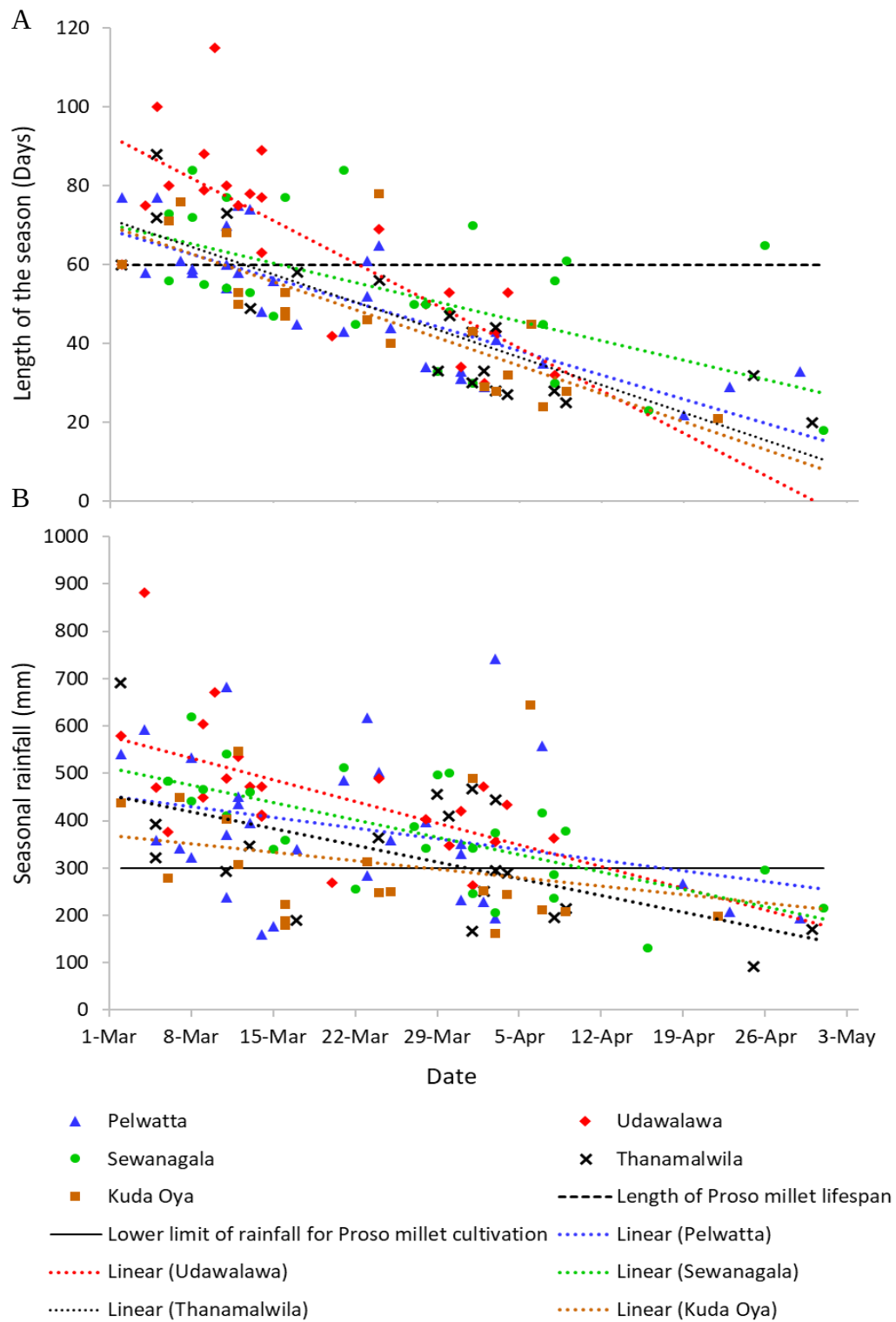


Figure 3.6. The relationship between (A) onset and length of the season and (B) onset and the seasonal rainfall in Proso millet growing region of Sri Lanka for 1983–2015 period. The horizontal black line in (A) is the typical length of Proso millet lifespan (60 days) and (B) is the lower limit of rainfall for Proso millet cultivation (Changmei and Dorothy 2014).

Other key information that would assist in agricultural planning is the relationship between onset and the amount of rainfall during a season. However, onset date and the amount of rainfall throughout the season did not show a significant ($p > 0.05$) relationship at Pelwatta and Kuda Oya, the wettest and the driest stations respectively in the study. In contrast, three other stations showed a significantly ($p < 0.05$) inverse relationship and recorded a higher seasonal rainfall for early onset dates (Figure 3.6B). A poor correlation ($r = -0.4799$) was observed between the onset and seasonal rainfall in Proso millet growing region in LCDZ, Sri Lanka.

3.4.7. Dry spells during the growing season

The probability of 7-day dry spells in a period of 30 days during the Proso millet growing season was plotted against the date of the year (Figure 3.7). Generally, all the stations followed a similar pattern, but they were significantly ($p < 0.05$) different among each other according to the non-parametric Kruskal-Wallis test. Based on the data studied, the highest probability of 7-day dry spells during the *Yala* growing season was recorded at Thanamalwila and Kuda Oya (Figure 3.7). The lowest probability of 7-day dry spell in Thanamalwila was from 22nd March to 29th March, during the data period and it is similar to the mean (29th March) and median (28th March) sowing dates reported from the on-farm field survey. It was recorded that Proso millet farmers in the area select the day with the lowest probability of potentially damaging dry spell to sow seeds that will reduce seed desiccation and increase plant emergence. It comes from their experience and none of the farmers checks the water availability by testing soil moisture in the field into a certain depth.

Proso millet fields near Thanamalwila and Kuda Oya experienced a higher probability (98% and 97% respectively) of 7-day dry spells at flowering stage, but the probability

of dry spells was comparatively low in Sewanagala (64%) and Udawalawa (59 %) during that stage. A higher probability of dry spells during reproductive and ripening stages was observed from Pelwatta, than Udawalawa and Sewanagala. The risk of 7-day dry spells was lower during the initial crop growth phases but increased with age. Proso millet plants at reproductive and ripening stages are more vulnerable to long-term dry spells.

Average growth stage development (1980–2009 period) of five Proso millet accessions that were simulated by calibrated and validated APSIM millet model (Chapter 4) was plotted against the probability of occurring 7-day dry spells (Figure 3.7). It was found that the probability of dry spells increased rapidly after emergence (growth stage 3) to flag leaf initiation (growth stage 6). The probability of dry spells was close to 1 from flowering (stage 7) to harvesting (stage 12). On average, all the days from the end of juvenile (stage 4) has a probability of more than 0.5 of occurrence within 7-day dry spells. Therefore, most part of the Proso millet lifespan is susceptible to dry spells.

Both seeds and seedlings of Proso millet can be damaged due to heavy rain and drought during the initial phases of the crop, causing uneven crop stand across the field or permanent loss of the crop. No evidence was found on re-sowing of Proso millet to fill the gaps in the study area, therefore, farmers maintain and harvest the remaining parts of the field. The strategy used by farmers to protect against unexpected damages was to maintain a high plant density, as described in Chapter 2. The amount and favourable distribution of rainfall during Proso millet growing period are key factors for a successful cultivation.

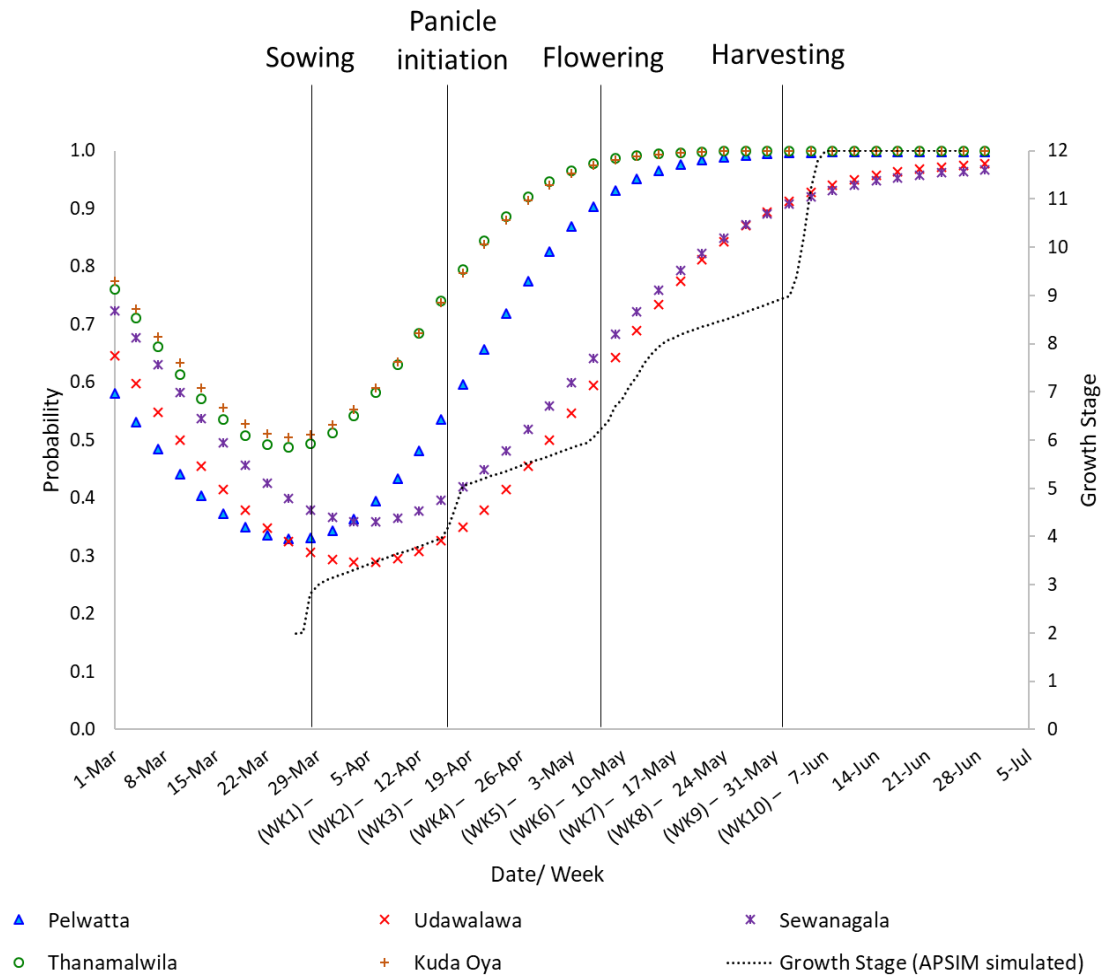


Figure 3.7. The probability of 7 days dry spells in a period of 30 days centred on a particular day during the Proso millet growing season in Low Country Dry Zone Sri Lanka for 1983–2015 period. All the dates marked in this figure are based on information from the farmer survey. The growth stages from APSIM simulation (Chapter 4) are as 1=sowing, 2=germination, 3=emergence, 4=end of juvenile, 5=floral initiation, 6=flag leaf, 7=flowering, 8=start grain fill, 9=end of grain filling, 10=maturity, 11=harvest ripe and 12=harvest. WK1 to WK10 represent the weeks after sowing.

3.5. Discussion

Rainfall amount and distribution determine the lifestyle of subsistence farmers in agricultural areas in Sri Lanka. All the farming activities in the Proso millet growing area were found to be heavily dependent on the amount and the distribution of rainfall which agrees with the findings of Gunarathna et al. (2004).

Previous work on growing seasonal characteristics of the LCDZ in the southern plains of Sri Lanka was almost non-existent, therefore this analysis can be used to make recommendations for farmers in those areas. Previous studies of Punyawardena (2002) recorded that onset and retreat of *Yala* season in the North Central Dry Zone that belongs to the DL_{1b} AEZ were in late March (13th week) and in late April (between 18th – 19th week) respectively. Observed mean onset (12th week) and retreat (20th week) in the Proso millet growing region were different from the findings of Punyawadana (2002) by one week. The mean of 7.4 week length of growing season across Proso millet growing area was much higher than the 5 week period reported by Punyawadana (2002). In contrast to the Proso millet growing area, FIM and SWM are not prominent in the North Central part of the country (Punyawardene 2008) and can be suggested as the reason for discrepancies in onset, retreat and the length of the season.

Both increasing and decreasing rainfall trends were observed in Sri Lanka in different timescales (Malmgren et al. 2003; Jayawardene et al. 2005; De Costa 2008; Muthuwaththa and Liyanage 2013; Wickramagamage 2015). Long term (1869–1987) rainfall trend analysis at Hambanthota in LCDZ reported an increasing trend (Jayawardene et al. 2005) as reported in the current study for the region. Rainfall trends for monsoonal seasons revealed in the study agree with the finding of Wickramagamage (2015), on which SWM rainfalls were negative throughout Sri Lanka whereas inter

monsoons and NEM had positive trends. With the increment of FIM rainfall to the area, there is a possibility to shift Proso millet cultivation backwards in *Yala* season. Seed system, cultivation of other cash crops and market problems avoid this falling Proso millet cultivation at a risk in the future.

Sri Lankan climate is divided into two cultivation seasons by different timescales as identified in different studies (Zubair 2002; De Silva et al. 2007; Chithranayana and Punyawardena 2008; Sonnadara 2015). However, it was found that the actual growing season that supports crop cultivation is far below the hypothetical growing season reported in most studies. Rainfall retreats 11–15 weeks before the generally accepted end to growing season (*Yala*) defined in the literature. Southwest Monsoon rainfall is not clearly observed in the area (Punyawardena 2008) and creates water scarcity during the latter part of *Yala* that limits the options for crop cultivation in the Proso millet growing region in June onward.

Since the first rain event is not always followed by the onset of the rainy season in the area (Figure 3.5), dry spells could occur during the vegetative stages of Proso millet. Therefore, it is worth to distinguish the dry spells to avoid the false onset when identifying the best sowing date. Marteau et al. (2011) investigated the relationship of rainfall onset and farmers' sowing strategy for Pearl millet cultivation in Southwest Niger finding that most farmers waited for the first rain event before sowing whereas a few of them sow seeds before the rains, i.e. when the soil is dry. This is called 'dry seeding' and allowed farmers to get more arable lands sown at the time of onset and reduce time-consuming land preparation after the first useful rain. On the other hand, this technique has a higher possibility of having poor plant establishment due to damage caused by insects, birds, and seed desiccation (Liboon et al. 2001).

Some other Proso millet farmers avoid seeding at the start of the rainy season to protect seeds from heavy rain. The inability to sow in a rainy day, with farmers reporting this could be due to delay in land preparation, or social and religious activities, lead to dry seeding of Proso millet. But, the dry seeding is not a farming technique followed by Proso millet farmers in Sri Lanka as an adaptation strategy to rainfall variability and to the labour shortage, such as commonly practised in Niger (Marteau et al. 2011). The date of seed broadcasting varied within a couple of weeks in the same area, but discussions with farmers and survey results revealed that the sowing date solely depends on rainfall. Therefore, any changes in the onset of the rainy season will affect the Proso millet cultivation in the area.

Different crop growth stages are sensitive to water availability in different ways. In Proso millet, the floret death and lowering of seed weight that reduces the harvest index is the major impact caused by the drought stress at ear emergence stage (Seghatoleslami et al. 2008). Avoidance of moisture stress at ear emergence and flowering by the possible shift of the sowing date to a later date is limited by variation in the onset date because false onset can damage the crop in early stages. The higher probability of long term dry spells during the reproductive stage (Figure 3.7) that limits water availability in the most sensitive growth stage can be the reason for observed lower yield recorded from yield analysis in Chapter 2. Therefore, it is important to study the impact of rainfall distribution on yield and the environmental factors that causes yield variation using multi-year data.

Delayed onset of rainfall is one of the major climate related agricultural issues that responsible for abnormal cropping calendar, crop failure and yield reduction in Intermediate Zone (IZ) Sri Lanka (Esham and Garforth 2013). Change in planting dates, changing crop varieties and crop rotation were common adaptation strategies practised

in Mid Country Sri Lanka to bypass the critical crop growth stages from overlapping dry periods (Esham and Garforth 2013). The comparatively shorter length of the growing season than that which occurs in the Wet and IZ, low water availability and high variability of rainfall in the area (Punyawardena 2002) limit the usage of these management practices in Proso millet growing region in Sri Lanka. Changing planting date is a no-cost adaptation strategy that can be implemented at the farm level, but large shifts would affect the management of other crops grown during rest of the year (Mall et al. 2006). Furthermore, changes in cropping sequence and land use can be used as an alternative adaptation option under the changing rainfall pattern. In some regions, low availability of land areas limits the possibility of shifting Proso millet cropping fields, as it is most common in the *Chena* farming systems.

Due to the short rainy season in some areas, it is important to invest in soil water and nutrient management technologies for Proso millet cropping systems. But most of the Proso millet farmers are practising shifting cultivation inside small forest areas, therefore, it limits the possibilities of introducing new technology.

3.6. Conclusions

The selection of crops and crop management practices in Proso millet growing area in Sri Lanka coincided with the distribution of rainfall. The mean rainfall during Proso millet growing season throughout the study period (361 mm) is higher than the lower limit of rainfall (300 mm) where Proso millet gives a satisfactory yield, based on the literature. On average, 36.4% of Proso millet growing seasons in the growing region received less than 300 mm of rainfall during the study period. Long-term rainfall values indicated that all the stations belong to the Dry Zone of the country, but the total rainfall amount showed an increasing trend in the region. Date of onset was not significantly

different among stations and can be successfully used to predict the length of the season in Proso millet growing region in Sri Lanka. While crop selection and the timing of existing crop management practices seem appropriate for the distribution of rainfall, farmers in the region do not practice soil moisture conservation and water management. These strategies could be critical to reduce the risk of water-related damage in the susceptible flowering stage and for a successful Proso millet cultivation in Low Country Dry Zone Sri Lanka.

3.7. Chapter summary

- Rainfall distribution determines the agricultural pattern in Proso millet growing region in Sri Lanka.
- Definitions were developed to identify the onset and retreat of Proso millet growing season in Low Country Dry Zone Sri Lanka.
- Annual rainfall amount in the region showed an increasing trend for 1983–2015 period.
- Length of the season can be predicted successfully using the onset date.
- Farmers adjust crop management practices and crop selection to minimise the climate associated damages to Proso millet cultivation.

Chapter 4

Calibration and validation of APSIM millet model for five Proso millet (*Panicum miliaceum* L.) accessions collected from Sri Lanka*

4.1. Introduction

The climate associated risk is a serious issue to crop production (Lobell and Field 2007). The climate sensitivity of the crops, the impact of climate change towards agriculture and the productivity of crops under future climates can be studied using crop modelling approaches (White et al. 2011; Karunaratne et al. 2015; Zubair et al. 2015). Crop models also used to evaluate agricultural adaptation options by both policymakers and local stakeholders (Oteng-Darko et al. 2013; Rauff and Bello 2015). Genetic coefficients of crops are essential to simulate different crop species and varieties (Jame and Cutforth 1996). Therefore, the lack of these coefficients for several crops has hindered crop modelling applications.

As described in Chapter 2, Proso millet is identified as a drought tolerant crop that will produce sufficient yield in unfavourable environments to other crops (Habiyaemye et al. 2017). No systematic studies on climate sensitivity, adaptation and yield potential were carried out on Proso millet in Sri Lanka, thus the information on the yield response to climate and crop management practices could help farmers on decision making to

* The chapter based on the manuscript (under review): Wimalasiri GEM, Ashfold MJ, Walker S, Nissanka SP, Karunaratne AS. 2018. Calibration and validation of APSIM millet model for five Proso millet (*Panicum miliaceum* L.) accessions collected from Sri Lanka. Crop and Pasture Science.

increase the yield of Proso millet. Therefore, research attention on modelling applications of Proso millet is important.

But Proso millet in Sri Lanka or other growing regions that is cultivated as subsistence crop was not studied using modelling approaches previously. Also, genetic coefficients and other generic parameters of Proso millet accessions/ landraces were not recorded in the literature. Once a crop model is calibrated and validated, it can be used to study the climate sensitivity and yield projections of Proso millet as described in Chapter 5. Therefore, a crop model was calibrated for Proso millet initially, and the model was used to study the future Proso millet yield and climate sensitivity in growing regions in Sri Lanka (Chapter 5).

The objectives of Chapter 4 were (i) to compare the phenology, leaf area index, above ground biomass and yield of five Proso millet accessions originated from farmer fields in the Dry of Zone Sri Lanka (Chapter 2); ii) to calibrate the APSIM millet model for selected Proso millet accessions and (iii) to validate the calibrated model for farmer fields in Sri Lanka. The calibrated and validated model will be used to study the climate sensitivity and yield projections of Proso millet in Sri Lanka (Chapter 5), as mentioned earlier.

The chapter describes important aspects of the literature on crop modelling and Agricultural Production Systems Simulator (APSIM) as a crop modelling tool (section 4.2), methodologies (4.3), results (4.4) and discussion (4.5) on model calibration and validation. Section 4.6 concludes the chapter.

4.2. Crop model applications

The use of crop modelling approaches to study crop growth and development, yield and decision making in agriculture have increased in the last decade (Ahmed et al. 2013; Holzworth et al. 2014; Paola et al. 2016). Section 4.2 reviews the definition, uses and constraints of crop modelling, different modelling platforms, APSIM model and previous modelling attempts of Proso millet.

Crop modelling has been defined by different scientists in different ways. A model is a mathematical representation of a real system (Ahmed et al. 2013) or simulation of a set of equations which clarifies the behaviour of a system and helps to understand and improve the performance of the system (Oteng-Darko 2012; Rauff and Bello 2015). Monteith (1996) defined a crop model as a quantitative way of predicting crop growth, development and yield under defined genetic coefficients and relevant environmental variables. Crop simulation models predict plant growth and development in a given environment under specified crop management practices with available information on soil, plant ecophysiology and climate (Hodson and White 2010).

Crop models can be categorised into different clusters depending upon the purpose for which they have been designed (Murthy 2003). Mechanistic crop models have physical or physiological basis and describe the nature of a system from lower level elements with the mechanism whereas empirical models consist with functions selected to fit the measurements from field or laboratory and generally shown as regression equations with one or few factors (Monteith 1996; Oteng-darko et al. 2013; Rauff and Bello 2015).

Modification of parameters of a model to capture the main features of an observed crop system with minimised error is model calibration while confirmation of the close

representation of the calibrated model to the real situation is model validation (Boote et al. 1996; Oteng-Darko et al. 2013).

4.2.1. Uses and limitations of crop models

Once carefully calibrated and validated, crop models are very useful to evaluate the performance of agricultural systems under different management and environmental conditions (Amarasingha et al. 2014). Crop models are helpful in different ways; forecasting of growth and development of crops (Marcelis et al. 1998), nutrient dynamics (Madegwa 2015), to study the physiological and environmental relationships with crops (Tardieu and Tuberosa 2010; Mangin et al. 2017), plant breeding (Li et al. 2012), climate sensitivity of crops (Wang et al. 2009; Ruane et al. 2014; Karunaratne et al. 2015), yield forecasting (Zubair et al. 2015) and study climate change impact and adaptation (Sultan et al. 2013; Webber et al. 2014). Agrometeorological importance of crop modelling has been widely accepted (Betts 2005; Rauff and Bello 2015).

Limited validity is the most common problem in crop modelling. Crop models are site and crop specific, therefore, application of the model ahead of the conditions they were originated and tested is an inherent risk of models (Monteith 1996). Before use in areas other than they are calibrated, these models should be validated under the local conditions (Ahmed et al. 2013). Insufficient understanding of natural processes will lead to inaccurate projections in crop modelling (Oteng-Darko et al. 2013). Unavailability of accurate input data such as appropriate weather data, soil characteristics, water balance and management factors will also limit the model use (Boote et al. 1996).

4.2.2. Decision Support Tool: Agricultural Production Systems Simulator (APSIM)

Various types of crop models are designed to simulate the growth and development of crops and agricultural systems. Some of the famous crop models are Agricultural Production System Simulator – APSIM (McCown et al. 1995), Decision Support System for Agrotechnology Transfer – DSSAT (Jones et al. 2003), CROPwat (FAO 2009), AquaCROP (FAO 2011) and System for Regional Analysis of Agro-Climatic Risks – SARRA-H (Baron et al. 1999).

Among several crop modelling tools currently available, APSIM is one of the widely used simulation tools for modelling agricultural production systems across the world (Holzworth et al. 2014). It was developed by Agricultural Production Systems Research Unit (APSRU), a collaborative group from CSIRO and Queensland State Government agencies. APSIM simulates the biophysical process in farming systems, concerning the economic and ecological outcomes of management practice with climatic risk and has been applied over a wide range of crops and environments across the world (Keating et al. 2003; Holzworth et al. 2014).

APSIM has been used worldwide in a wide range of applications, including supporting on-farm decision making, to simulate the performances of different crops under diverse management decisions, designing farming systems, to analyse risks and to assess seasonal climate forecasting, supply chain analysis in agri-business, waste management guideline development and as a research guide (Keating et al. 2003).

Model intercomparison studies have shown that crop models perform in different ways at the field scale due to different approaches used in the models (Palosuo et al. 2011; Salo et al. 2016). The simulation of crop physiological processes in APSIM uses the

concept of supply and demand balances for light, carbon, water and nitrogen (Hammer et al. 2010). The nitrogen cycle can be explicitly simulated by APSIM (Sultan et al. 2014) which enables the use of this crop model to study the impact of nitrogen. APSIM is one of the few models that simulate the processes on phenological response to N stress (Salo et al. 2016). APSIM has also been successfully used to simulate C₄ crop production in Africa (Turner and Rao 2013, Akponikpè et al. 2010).

APSIM applications in Sri Lanka were mainly reported on field crops and has been used for different purposes; to model the effect of water stress on paddy yield (Kumara et al. 2014), to evaluate the irrigation water requirement and yield of the maize-mung bean inter-cropping system (Amarasingha et al. 2015a), to study climate change impacts on rice farming (Zubair et al. 2015), to assess crop productivity of medium and short duration rice varieties in rainfed systems (Amarasingha et al. 2015b) and to simulate crop and water productivity for rice under different agro-climatic systems and water management techniques (Amarasingha et al. 2015c). APSIM model calibration (rice – Nissanka et al. 2015) and validation (rice – Fernando et al. 2015) using Sri Lankan data have been previously documented.

The millet module of APSIM was developed based on the growth and development of Pearl millet (*Pennisetum americanum*) crop (van Oosterom et al. 2001a, 2001b). No documents were reported on the use of APSIM millet model in Sri Lanka, even though the model was tested for wide range of environments for decision making regarding nitrogen management for pearl millet in the Sahel (Akponikpè et al. 2010), response of nitrogen fertilisation on the grain yield of pearl millet in India (O’Leary, 2008), nutrient dynamic of finger millet fields in semi-arid Kenya (Madegwa 2015) and to assess future climate risk for family food self-sufficiency (Pearl millet) in Mali (Traore et al. 2017).

4.2.3. Previous modelling of Proso millet

Very few attempts were made on modelling of Proso millet crop. Andales et al. (2003) simulated Proso millet grain yield, crop residue and soil nitrogen to study the performance of crop rotation in the USA using “Great Plains Framework for Agricultural Resource Management” (GPFARM) Decision Support System. The model was calibrated using the observed maximum leaf area index and potential harvest index (Andales et al. 2003). The CSM–CERES–Sorghum module in DSSAT v4.0 was calibrated for Proso millet in Central Great Plains to study the response of summer fallow crops to plant available water at planting (Saseendran et al. 2009). Leaf area index, grain yield, biomass and soil water were used to calibrate the model. The model was validated using data from the same experimental field (Saseendran et al. 2009). A software PhenologyMMS simulates the phenological responses of Proso millet to water stress in the Great Plains, USA (McMaster et al. 2011). The same data set of Saseendran et al. (2009) were used to simulate yield and economic net returns at different plant available water levels in dryland winter fallow system in the Great Plains using The Root Zone Water Quality (RZWQM2) model (Saseendran et al. 2013).

As a summary for the section 4.2, crop modelling approaches can be successfully used to evaluate the performance of agricultural systems, forecasting of growth and development, yield projections and climate sensitivity of crops. However, Proso millet in Sri Lanka or other growing regions that is cultivated as subsistence crop was not studied using modelling approaches previously. Also, APSIM crop model was not tested for Proso millet crop. Farmer selected Proso millet accessions were also not simulated and the calibrated models found in the literature were not validated from the real field observations (farmers’ data). Therefore, the following methodologies were

used to calibrate and validate the APSIM millet model for five Proso millet accessions collected from farmers' fields in Dry Zone Sri Lanka.

4.3. Methodology

4.3.1. APSIM millet module description

As APSIM is not parameterised for Proso millet, the millet module that was developed based on Pearl millet was used as a proxy. The method followed by Madegwa (2015) for finger millet simulation was used to select the crop model. Similar ecological, functional and agronomic characteristics of both millet types (Krishna 2013) make pearl millet a suitable substitute for Proso millet for APSIM simulations.

Daily growth and development of Pearl millet crop is simulated in APSIM millet model (van Oosterom et al. 2001a, 2001b, 2002). It was parameterised based on the field experimental data from ICRISAT–Patancheru, India (van Oosterom et al. 2001). The model is specially designed to capture the tillering habit of the crop. The main difference with other crop models in APSIM is that growth and development of individual tillers can be simulated in the millet model while the entire crop is considered as an intercrop of different axes. The model is capable of adequately predicting leaf area index, biomass and grain yield over a range of photoperiods and genotypes (www.apsim.info; Keating et al. 2003; Holzworth et al. 2014). The flow diagram of the daily processes of APSIM millet model is shown in Figure 4.1.

In order to simulate the millet crop, it needs site specific climate data (temperature, rainfall, radiation) for meteorological models, soil properties and crop management data (such as date of planting, fertiliser application dates and amounts). The model responds to soil nitrogen (soiln2 module) and soil water supply (soilwat2 module). In

phenology of millet module, there are 11 crop growth stages and thus, 10 growth phases namely, sowing, germination, emergence, end of juvenile, floral initiation, flag leaf, flowering, start grain fill, end of grain filling, maturity and harvest ripe. Soil moisture controls sowing to germination stages while the accumulation of thermal time determines all other growth stages. The daily thermal time is decreased by nitrogen or water stress between emergence and flag leaf stages, that delays phenology.

Daily biomass accumulation is a function of soil water (for transpiration) and radiant energy. Water content among all soil layers (where roots present) and crop water demand are used to calculate transpiration. Accumulation of thermal time or biomass determines the rate of tiller appearance, that depends on the space between plants. Competition to light and stresses caused by temperature and water make leaf senescence. Residues pass to other modules (residue2 and soiln2) once the crop is harvested (www.apsim.info; Keating et al. 2003). The model details on phenology, leaf area index and biomass accumulation will be further described in sections 4.4.3 and 4.4.4.

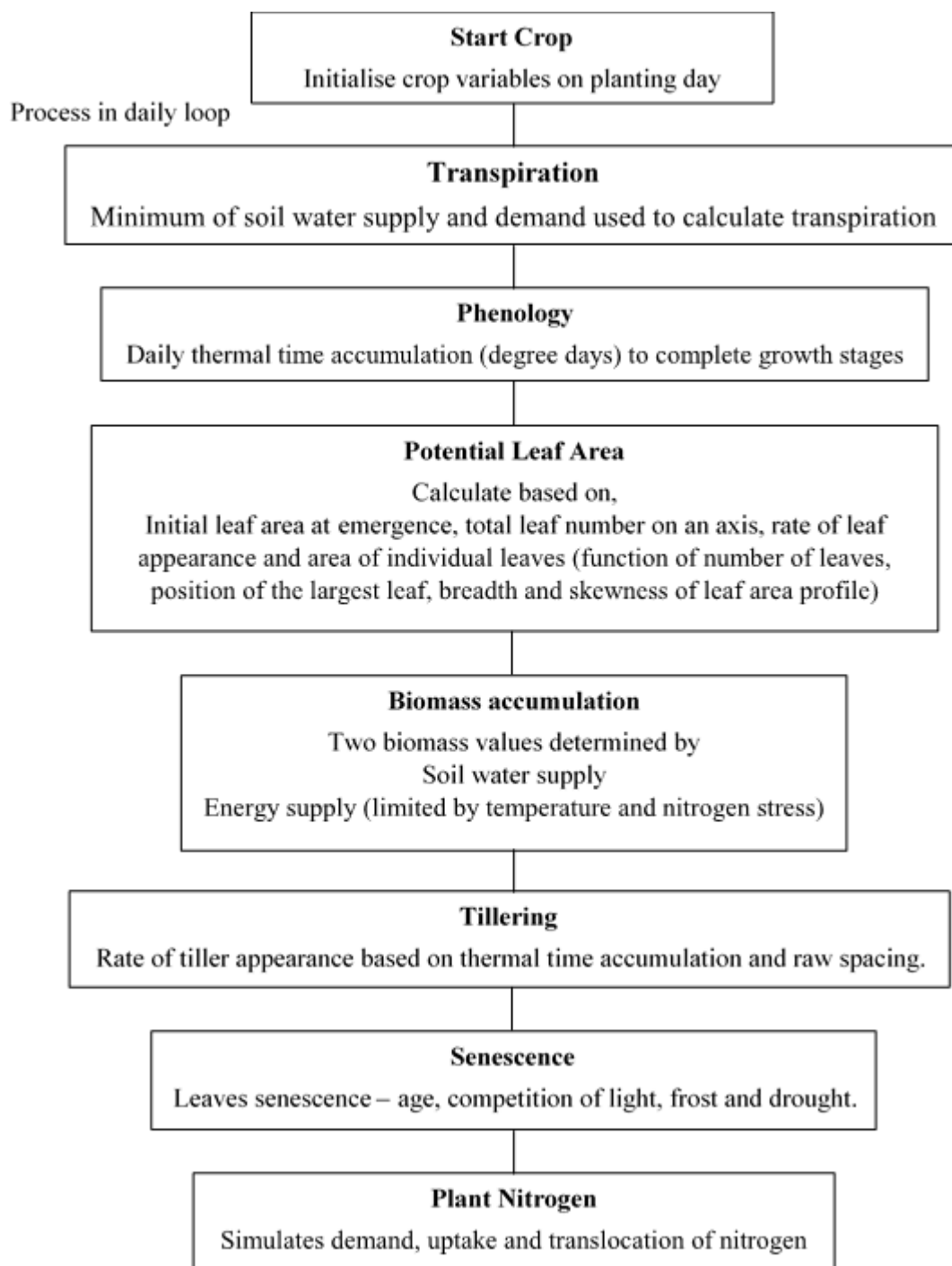


Figure 4.1. The flow diagram of the daily processes in APSIM millet model.

4.3.2. Selection of Proso millet accessions

Distinct Proso millet seed samples (hereafter mentioned as accessions) used in calibration experiments were selected to represent different seed sources and locations in Proso millet growing regions (6.41–6.44°N, 81.08–81.12°E) of Moneragala and

Hambanthota districts in Sri Lanka (Chapter 2). They were grown in different soils under diverse management practices (Chapter 2). All farm fields belong to DL_{1b} agroecological zone and climate characteristics of the area were previously described (Chapter 3). Seeds from individual panicles were selected from each farmer field and defined as distinct Proso millet accessions. They were named as L_1, L_11, L_12, L_14 and L_25, based on the sample collection sites using the Global Positioning System for site identification (Table 4.1).

4.3.3. Experimental details

The data for model calibration and validation were from two types of studies; the model calibration was done using data collected during two detailed field experiments conducted at the Sabaragamuwa University of Sri Lanka, and model validation was done using farmer survey data and harvest collection data from farmers' fields (Chapter 2).

Calibration experiments

Calibration Experiment 1

Data for model calibration were derived from two field experiments conducted at the Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka (SUSL), Belihul Oya (6.70°N, 80.79°E; 610 m altitude). The area receives more than 1600 mm of rainfall annually distributed over two monsoons and two inter-monsoons. The prominent rainy season in the area is the Northeast monsoon that falls from December to February (Punyawardena 2008). The annual average temperature is 27 °C. The major soil type is Immature Brown Loam that belongs to Mahawalatenna series and the great group of Endoeutric Cambisols (Mapa et al. 2005).

Table 4.1. Geographical distribution and an average yield of selected Proso millet accessions in the calibration experiment.

Accession number	Latitude (°N)	Longitude (°E)	Village	Yield (kg ha ⁻¹) *
L_1	6.4075	81.0883	Angunakolawewa	1682±555
L_11	6.4177	81.1118	Wadiyawaththa	676±294
L_12	6.4339	81.1052	Komaligama	1400±358
L_14	6.4372	81.0883	Meegaswewa	1320±42
L_25	6.4379	81.0911	Adarsha Gammanaya	1377±444

* Yields in Table 4.1 were calculated from the harvest of the previous growing season (Yala 2015).

The Calibration Experiment 1 was carried out during a drier period; August–October 2016 (total rainfall 4.5 mm, mean temperature 27.1 °C). The land was deep ploughed by mouldboard plough to loosen the compacted soil. Approximately at a rate of 1000 kg ha⁻¹ of cow dung, 750 kg ha⁻¹ of goat dung and 500 kg ha⁻¹ of biochar prepared from paddy husks were evenly distributed throughout the experimental field 10 days before planting. The field was ploughed again by rotavapor to mix the soil and organic matter, and experimental unit (plots) of 1 m x 3 m were prepared. As the treatment, five Proso millet accessions was laid out in a Randomised Complete Block design with three replicates. Figure 4.2 shows the calibration experimental field at SUSL.

Due to a low number of seeds from plants collected by farmer fields and low germination percentage, a germination method used by paddy farmers in Sri Lanka was

used to plant the crop. Proso millet seeds were soaked in water for 24 hours, drained and allowed to germinate. Germinated seeds were then sown in plug trays and raised for 14 days. A mixture of coir dust, sand, cow dung and soil into 1:1:1:1 ratio was used in plug trays.

Recommended fertiliser amounts were applied 2 days before transplanting, as 125 kg ha⁻¹ of Urea, 50 kg ha⁻¹ of Concentrated Super Phosphate and 50 kg ha⁻¹ of Muriate of Potash (Department of Agriculture Sri Lanka – DOASL: www.agridept.gov.lk). Proso millet seedlings were transplanted into the field 14 days after sowing (DAS) at 10 cm distance in rows spaced 15 cm apart. Temporary shade was provided for two days to protect plants from the heavy sun. Urea was applied at the rate of 75 kg ha⁻¹ 14 days after transplanting. Plants were protected against pests by both chemical and physical methods. Fipronil 16 mL/16 L and Abamectin 18 g/L EC were sprayed to control red spider mites (*Tetranychus spp*) and thrips (*Cirtothrips dorsalis*) respectively.

The mosquito net was laid around the plots to protect plants from birds and other large pests. Panicles were covered by tissue papers to avoid cross pollination. An adequate amount of irrigated water was provided on a daily basis to grow Proso millet plants without water stress conditions.



Figure 4.2 (A) Calibration experimental field at the start of the experiment and (B) field covered by a mosquito net to protect from birds.

Calibration Experiment 2

Experiment 2 was carried out during a rainy season (February–April, total rainfall 492.5 mm, mean temperature 26.3 °C) in 2017. Harvested seeds of experiment 1 were used in experiment 2 to raise crops. All the land preparation, fertiliser application and crop management practices were similar to experiment 1 while germinated seeds were directly planted in the plots (did not use plug trays). Urea (75 kg ha⁻¹) was applied 14 days after planting. Due to a drier period at the start of the crop, the crop was irrigated from sowing to 10 DAS. Otherwise, the crop was grown as rainfed.

In both experiments, five representative well-bordered plants were selected randomly from each plot and tagged (Figure 4.3). From each tagged plant, a number of tillers, fully expanded and senesced leaves were counted twice a week from 3 Days After Emergence (DAE) until harvest. Dates of 50% germination, emergence, flag leaf emergence, heading (panicle visible), flowering, start of grain filling, maturity and harvest ripe were measured as phenological data. Leaf area development was measured in weekly intervals. For growth and dry-matter distribution analysis, randomly selected 3 plants from each plot were uprooted weekly and separated into different plant parts, oven dried for 48 hours at 80 °C temperature and dry weight was measured. Non-destructive method (length and width measurement) was used to measure the leaf area of tagged plants in the field. Leaf area of uprooted plants was measured from leaf area meter (LI-3100C Area Meter, LI-COR Inc. Lincoln, Nebraska USA). Proso millet plants were harvested at full maturity stage. Grain yield and weight of 100 seeds (with 3 replicates) were used to calculate grain number (van Oosterom et al. 2002).

Harvest collection from farmer fields for model validation

Proso millet harvest was collected from 41 farm fields in Bodagama Sri Lanka (6.41–6.44°N, 81.08–81.12°E) during 23rd May to 4th June 2015 as described in Chapter 2. Therefore, the details of the experiment, sample collection and measurements were not described here.

4.3.4. Calibration of APSIM crop model

To ensure the suitability of millet module, simulations were conducted using various crops (barley, maize, sorghum) to select the best matched phenological stages, yield and biomass. It was found that the millet module was the closest to Proso millet phenology and yields. The Pearl millet cultivar *hhb67* was selected as the base following similar procedures.

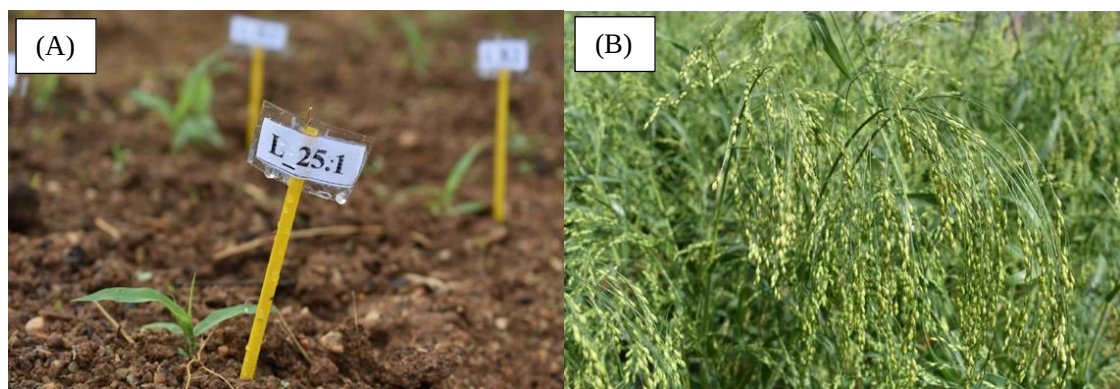


Figure 4.3 (A) Tagged Proso millet seedlings in the calibration experiment and (B) well-grown plant with panicles.

Calibration of APSIM – millet, Version 7.8 was undertaken for the five Proso millet accessions (L_1, L_11, L_12, L_14 and L_25) collected from farmers' fields in Sri Lanka. Soil properties were adjusted based on the measurements (Table 4.3). The crop phenology was simulated using thermal time (growing degree days – GDD). In the APSIM millet model, thermal time was calculated using the temperatures of 10 °C, 33 °C and 47 °C for base, optimum and maximum temperatures respectively (van Oosterom et al. 2011b). The cardinal temperature values were adjusted for Proso millet crop as; base temperature of 10 °C (Anderson 1994; Lyon et al. 2008), optimum of 30 °C and maximum of 45 °C. The plant density was set as 67 plants m⁻².

APSIM millet module was calibrated to match the observed and simulated phenology. The calibration procedure was initiated with the data gathered from the experiment 1 (irrigated) and fine-tuned with experiment 2 (mostly rainfed). The trial and error method was used to derive the best fit curve by matching the simulated dates of emergence, flag leaf, flowering, start grain fill, maturity and harvest ripe to the observed dates. Then, the calibrations were done based on the comparison between observed and simulated yield and above ground biomass. All the simulations in calibration were performed with the assumption that the crop is not water stressed. The best fit with minimum differences between observed and simulated yield was determined by adjusting the potential grains per head since the number of grains is a function of the millet yield (van Oosterom et al. 2002). Genetic parameters of five Proso millet accessions that were adjusted to match the crop phenology are summarised in Table 4.2.

Table 4.2. Accession specific parameters used to calibrate five Proso millet accessions L_1, L_11, L_12, L_14 and L_25 grown in experimental fields of the Sabaragamuwa University of Sri Lanka under optimum water and nutrient conditions.

Parameter	Unit	L_1	L_11	L_12	L_14	L_25
Potential grains per head	grains/head	2940	2645	3140	2795	3210
Potential grain growth rate	mg/grain/d	0.61	0.61	0.61	0.61	0.61
TT from emergence to end of juvenile phase	°C days	348.5	322	345	331	339
Photoperiod sensitivity	°Cd/h	112.4	112.4	112.4	112.4	112.4
TT from flowering to maturity	°C days	440	466	437	450	457
TT from flag leaf to flowering	°C days	85	90.5	94	87	70
TT from flowering to start grain fill	°C days	83	80	86	91	95
TT from maturity to harvest ripe	°C days	1	1	1	1	1

4.3.5. Model validation

The model was tested using the yield data gathered from farmers' fields at Bodagama Sri Lanka. The 30 farmer fields that have clear information on seed sources were selected and clustered into five accessions based on the similar seed sources. The millet module of APSIM has been parameterised for different plant densities ranging from 2.5 to 20 plants m⁻² and no density effect was recorded for grain yield and biomass (van

Oosterom et al. 2001a, 2002). The highest tested plant density (20 plants m⁻²) by van Oosterom et al. (2011a) were used in model validation.

A number of methods were used to compare the goodness-of-fit between observed and simulated values and to evaluate the model performance. The systematic behaviours of graphs were visually evaluated. The coefficient of determination (R²) determines the strength of the linear relationship between the observed and simulated values. The Nash and Sutcliffe (1970) model efficiency criteria, hereafter mentioned as N–S, was used to measure the efficiency of the model.

$$N - S = 1 - \frac{\sum_{i=1}^n (M_i - S_i)^2}{\sum_{i=1}^n (M_i - \overline{M})^2} \quad \text{Equation 4.1}$$

N–S is the measure of the mean square error to the observed variance (Karunaratne et al. 2010). The model represents a perfect fit if the error is zero (N–S = 1). If the error and observed variance are equal, then N–S = 0 and the observed mean value is as a good representation of the model. A negative N–S value indicates that the error about the model is greater than the error about the mean (very poor fitting model). Root Mean Square Error (RMSE) was used to measure the differences between observed and simulated values:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (M_i - S_i)^2}{n}} \quad \text{Equation 4.2}$$

where,

n is the number of observations, M is measured values/ observed values and S is simulated values.

4.3.6. Data analysis

Prism (Version 7.03) was used to perform ANOVA and t-tests and Microsoft Excel package was used to plot graphs.

4.4. Results

4.4.1. Soil properties of the calibration experiment site

Summary of measured soil characteristics for the experimental field at the Faculty of Agricultural Sciences, SUSL that were used as input parameters in APSIM model calibration are summarised in Table 4.3.

The mean bulk density values of the experimental field were $1.12 \pm 0.06 \text{ g cm}^{-3}$ (0–10 cm), $1.22 \pm 0.06 \text{ g cm}^{-3}$ (10–20 cm) and $1.35 \pm 0.15 \text{ g cm}^{-3}$ (20–30 cm). The bulk densities of different soil depths were not significantly ($p > 0.05$) different according to the Kruskal-Wallis non-parametric analysis of variance. Soil bulk density values were lower than the farmer fields but not significantly ($p > 0.05$) different.

Soil moisture content before planting were $29.39 \pm 2.04 \%$ (0–10 cm), $23.14 \pm 3.03\%$ (10–20 cm) and $20.84 \pm 1.11\%$ (20–30 cm), and the values were significantly different ($p < 0.05$) among depths. The soil moisture content was significantly ($p < 0.05$) higher than the farmer fields in the study area. The mean soil pH in the experimental field were 6.79 ± 0.06 (0–10 cm), 6.75 ± 0.10 (10–20 cm) and 6.74 ± 0.09 (20–30 cm). The pH values were not significantly ($p > 0.05$) different among depths. The soil is slightly acidic and close to the neutral value (pH=7). Soil pH values are higher than the farmers' fields in all the tested soil layers, but not significantly different ($p > 0.05$). A significantly ($p < 0.05$) higher EC was observed in the calibration field than the farmers' fields as the soil show EC of $171.9 \pm 54.6 \text{ } \mu\text{S cm}^{-2}$ (0–10 cm), $174.4 \pm 78.5 \text{ } \mu\text{S cm}^{-2}$ (10–20 cm) and

170.1±90.0 $\mu\text{S cm}^{-2}$ (20–30 cm). Soil EC values were also not significantly different ($p > 0.05$) among depths.

The soil in the calibration experimental field was ‘sand’ and ‘sandy loam’ according to the USDA soil textural class. The percentage of sand in the soil was not significantly different ($p > 0.05$) among depths. The clay content (ranged from 5.43 to 6.76%) of soil was higher than silt (ranged from 4.52 to 5.76%) in the experimental field and none of them was significantly different ($p > 0.05$) among soil depths. In soil textural properties, both sand and clay content were significantly different ($p < 0.05$) than the farmer fields. Comparatively higher total nitrogen content was reported in the experimental field than the farmers’ fields as it showed 0.80±0.32% (0–10 cm), 0.80±0.32% (10–20 cm) and 0.59±0.19% (20–30 cm) values, but they were not significantly different.

Table 4.3. Summary of measured soil characteristics of the experimental field at Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka

Layer (cm)	BD (g/cm ³)	Moisture content (%)	pH	EC (μS /cm)	Texture			USDA textural class	N (total) (%)	Munsell colour		
					Sand %	Clay %	Silt %			Hue	Value	Chroma
0–10	1.12±0.06	29.39±2.04	6.79±0.06	171.9±54.6	88.81±0.95	5.43±0.70	5.76±1.02	Sand	0.80±0.32	7.87 YR	4.5	1.6
10–20	1.22±0.06	23.14±3.03	6.75±0.10	174.4±78.5	89.84±1.02	5.64±1.00	4.52±0.21	Sand	0.80±0.32	7.63 YR	4.5	1.5
20–30	1.35±0.15	20.84±1.11	6.74±0.09	170.1±90.0	88.17±0.51	6.76±0.21	5.07±0.52	Sandy loam	0.59±0.19	7.47 YR	4.8	1.5

BD = Bulk density, EC= Electrical conductivity

4.4.2. Calculation of individual leaf area

Non-destructive method (length and width measurement) was used to measure the leaf area of tagged plants in the field. The leaf area was calculated using length and the maximum width of fully expanded leaves (van Oosterom et al. 2011a) as

$$\text{Individual leaf area} = \text{Length of the leaf} \times \text{Maximum width of the leaf} \times \text{Leaf shape factor} \quad \text{Equation 4.3}$$

The best-fitted regression equations were developed to estimate leaf area as a function of leaf length and maximum width in each accession for two growing phases; vegetative and reproduction (Figure 4.4).

The leaf shape factor (LSF) values that can be used to calculate leaf area were not significantly different ($p > 0.05$) among each accession during vegetative and reproductive phases. Mean LSF during vegetative and reproductive stages were 0.659 ± 0.077 (number of leaf samples 81) and 0.643 ± 0.078 (number of leaf samples 1580) respectively.

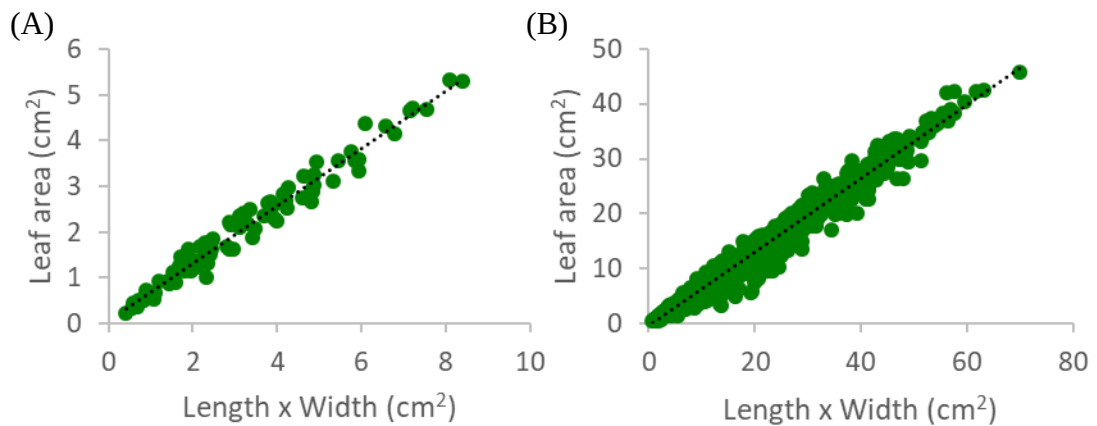


Figure 4.4. The relationship between measured leaf area and the product of length and maximum width during (A) vegetative and (B) reproduction phases of Proso millet. Green dots are the observed values and the dotted line is the linear relationship between the length x width and leaf area. A total of 81 and 1580 leaves were used respectively.

LSF values were also not significantly ($p > 0.05$) different among vegetative and reproductive growth phases. Generated LSF values were used to calculate leaf area values of Proso millet. No attempt was made to differentiate the relationships and LSFs between different accessions in the vegetative phase in leaf area calculation due to a low number of samples that leads to inaccurate estimations.

4.4.3. Calibration

Phenology

Model description

In the APSIM millet model, thermal time (in GDD) is calculated from the sum of 3 hourly air temperatures using linear interpolation of daily minimum and maximum temperatures. The GDD was calculated as followings

$$GDD = \sum_{t=3}^N DD_t, \quad DD = \begin{cases} 0 & \text{if } T_t < T_b \\ T - T_b & \text{if } T_b \leq T_t \leq T_o \\ T_o - T_b & \text{if } T_t > T_{opt} \end{cases} \quad \text{Equation 4.4}$$

where t represents three hourly time steps, N means the total hours in the season and DD is degree days. A base temperature (T_b) of 10 °C, optimum temperature (T_o) of 30 °C were used (Anderson 1994; Lyon et al. 2008).

Experimental results

The simulation of the phenology was the first aspect evaluated for five Proso millet accessions (L_1, L_11, L_12, L_14 and L_25) as thermal times were adjusted to calibrate the model. It was observed that flag leaf was visible in 625.5–673.5 GDDs, flowering at 725–759 GDDs, start grain filling at 792.5–837.5 GDDs and maturity at 1112–1136.5 GDDs. All the plants of five accessions were harvested at 1181–1222 GDDs (69 to 75 DAS).

Cumulative thermal time (GDD) to complete crop growth stages did not significantly ($p > 0.05$) differ among the 5 Proso millet accessions. Developmental stages of Proso millet showed a similar pattern in all tested accessions (Figure 4.5).

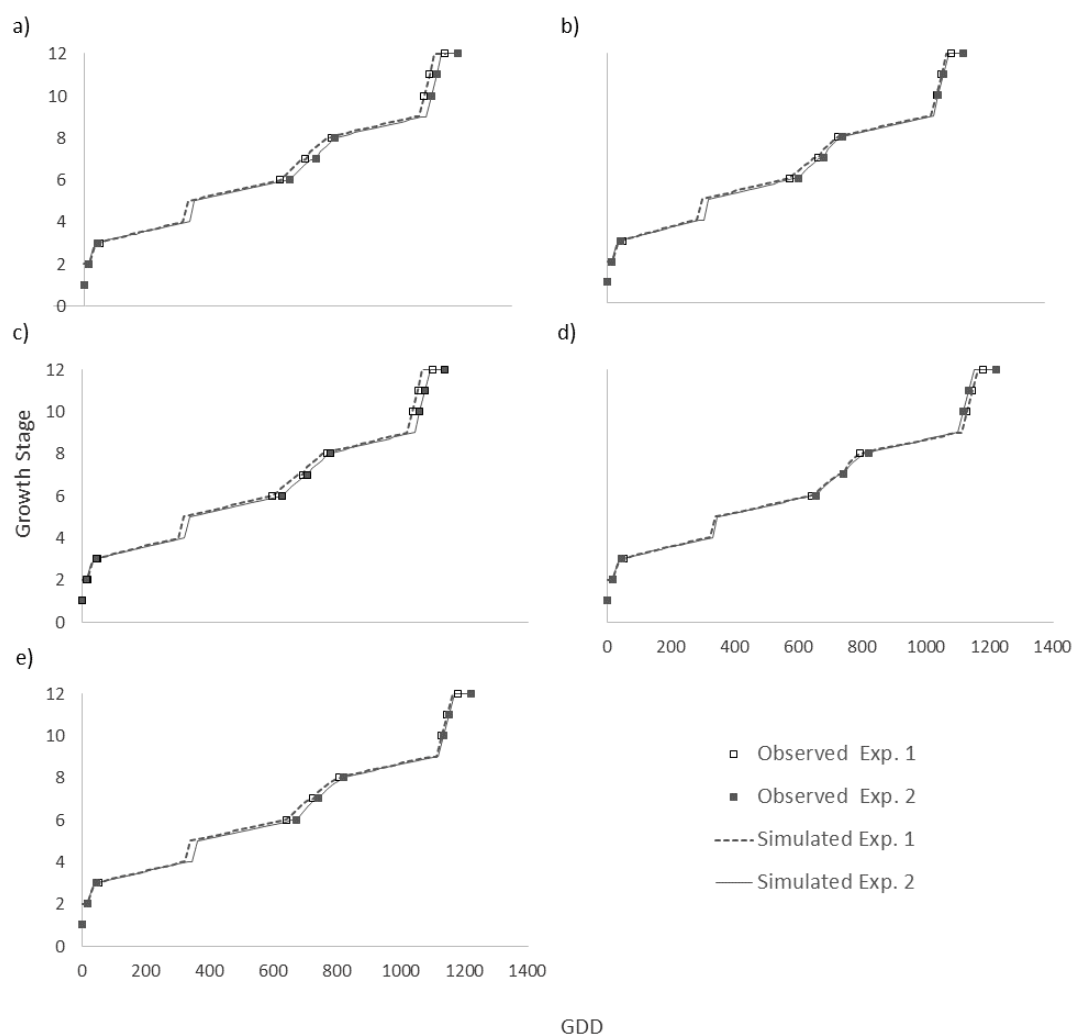


Figure 4.5. Comparison of simulated vs observed phonological development stages of five Proso millet accessions (a. L_1, b. L_11, c. L_12, d. L_14, e. L_25) express based on the cumulative thermal time (growing degree days; GDD). Developmental stages were defined based on APSIM millet module, where 1=sowing, 2=germination, 3=emergence, 4=end of juvenile, 5=floral initiation, 6=flag leaf, 7=flowering, 8=start grain fill, 9=end of grain filling, 10=maturity, 11=harvest ripe and 12= harvest.

4.4.4. Simulation of leaf area index, biomass and yield

Leaf area index

Model description

The area of individual leaf in the APSIM model is calculated from a bell-shaped function:

$$Y = Y_0 \exp(a(X - X_0)^2 + b(X - X_0)^3) \quad \text{Equation 4.5}$$

where Y and Y_0 are mature leaf area of individual leaf and the largest leaf respectively, X is the number of leaves and X_0 is the position of the largest leaf. The empirical constants a and b determines the breadth and skewness of the leaf area profile. The coefficients are functions of total leaf number (TLN). The mature leaf area of the largest leaf (Y_0) is genotypic, plant density and axis (main or tiller) specific while the other parameters are axis specific (Carberry et al. 1993; van Oosterom et al. 2001a).

Following equations (Equation 4.6 – 4.9) were used in APSIM model to calculate the variables in Equation 4.5 using TLN (van Oosterom et al. 2001a) as,

$$X_0 = 3.58 + 0.60 \text{ TLN} \quad \text{Equation 4.6}$$

$$Y_0 = 34.8 + 7.4 \text{ TLN} \quad \text{Equation 4.7}$$

$$a = 0.00955 + (0.0608 / (1 - 0.1293 \text{ TLN})) \quad \text{Equation 4.8}$$

$$b = 0.00144 + (0.0025 / (1 - 0.11 \text{ TLN})) \quad \text{Equation 4.9}$$

Experimental results

It was reported that the observed maximum leaf area index (mLAI) was highest in experiment 2 in all the accessions. The observed mLAI of experiment 1 ranged from 2.49 (L_1) to 2.94 (L_14). In experiment 2 mLAI ranged from 2.94 (L_1) to 3.19

(L_14). The simulation of LAI followed a similar pattern (Figure 4.6), i.e., the highest mLAI was from the experiment 2. It ranged from 3.58 (L_14) to 3.65 (L_25).

Leaf area index showed consistent overestimation in both simulations (calibration and finetuned experiment) during the vegetative stage and underestimation in the maturity stage (Figure 4.6). The simulated LAI was acceptable with a higher correlation coefficient (R^2) that ranged from 0.86 (L_11) to 0.99 (L_25) in experiment 1. In experiment 2, R^2 ranged from 0.86 (L_11) to 0.91 (L_12).

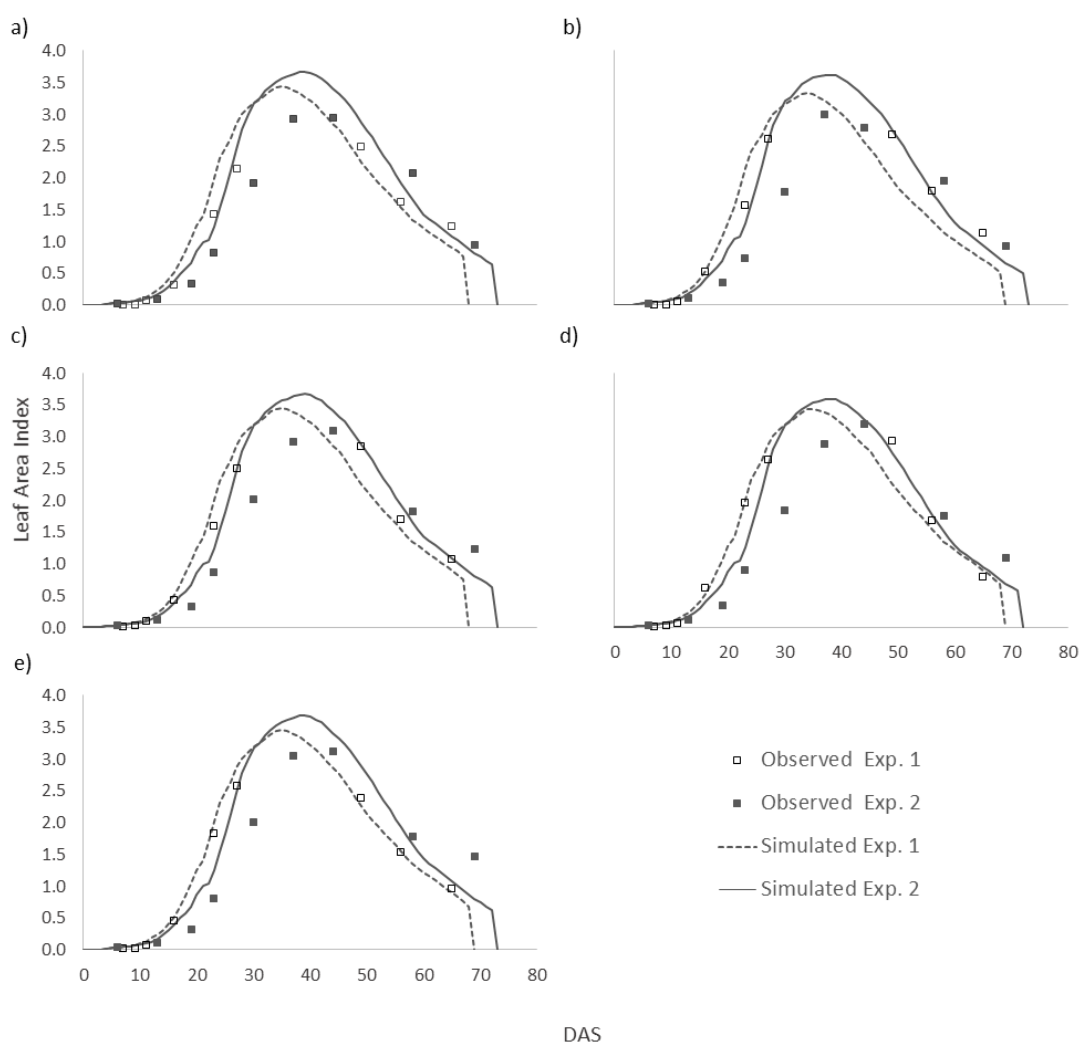


Figure 4.6. Comparison of simulated vs observed leaf area index development of five Proso millet accessions (a. L_1, b. L_11, c. L_12, d. L_14, e. L_25) from sowing (days after sowing (DAS)) of experiment 1 (2016–dry) and 2 (2017–rainy).

In average, a higher agreement between observed and simulated LAI was recorded from experiment 1 (dry period) than experiment 2 (rainfed). The LAI of accession L_12 was simulated by the fine-tuned model with higher accuracy (N-S 0.81, RMSE 0.52) than for other accessions. According to the non-parametric t-test, observed and simulated LAIs were not significantly different ($p > 0.05$) in all the accessions in both experiments.

Biomass

Model description

In the APSIM model, daily biomass accumulation is a function of water availability for transpiration (Equation 4.10) and radiant energy (Equation 4.11).

$$DM_{transp} = sw_supply_sum * TE \quad \text{Equation 4.10}$$

In this equation, the total water supply among all soil layers where roots are found is “sw_supply_sum”. The TE is transpiration efficiency, which is derived from the coefficient of TE (0.009) and vapour pressure deficit, that is based on daily temperature values. The soil water supply comes from soilwat2 module in the APSIM.

$$DM_{potential} = RUE * radiation_interception \quad \text{Equation 4.11}$$

The amount of light intercepted by the n axis in layer j of the canopy that will be used to simulate the growth, development and yield of millet is calculated using the extinction coefficient k (0.63) and LAI (van Oosterom et al. 2001a; van Oosterom et al. 2002) as,

$$f_{in} = f_j \left(\frac{k_j LAI_{jn}}{k_j (LAI_{j1} + \dots + LAI_{jn})} \right) \quad \text{Equation 4.13}$$

Experimental results

In simulations, the model overestimates the biomass compared to the observations in both experiments (2016 dry and 2017 rainy) in all the tested accessions (Figure 4.7). The observed biomass accumulation in five tested lines (L_1, L_11, L_12, L_14 and L_25) showed a similar pattern.

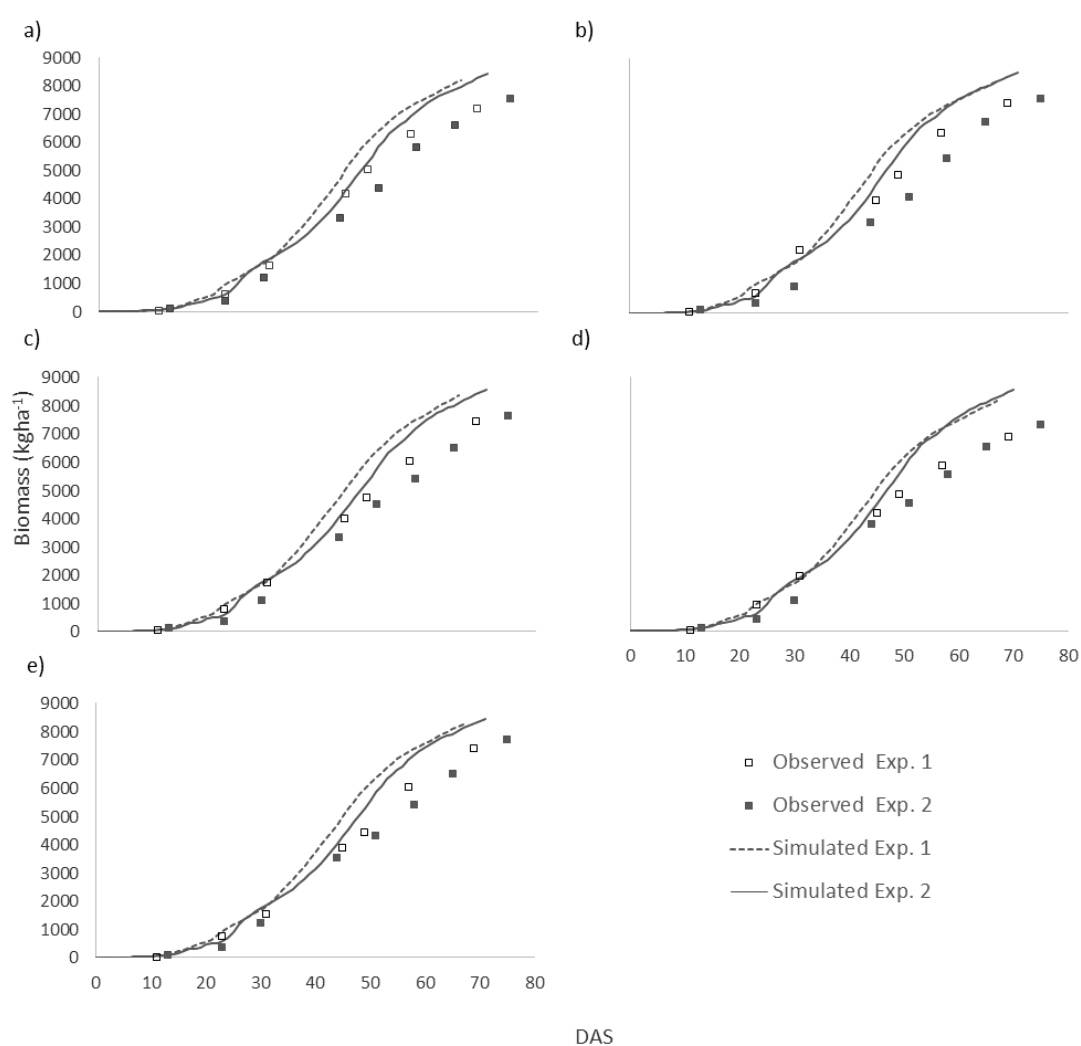


Figure 4.7. Comparison of simulated vs observed biomass accumulation of five Proso millet accessions (a. L_1, b. L_11, c. L_12, d. L_14, e. L_25) from sowing (days after sowing (DAS)) of experiment 1 (2016–dry) and 2 (2017–rainy).

The observed biomasses of all the accessions were higher in experiment 2 than experiment 1. The accession L_14 recorded the lowest biomass in experiment 1 (6893 kg ha⁻¹) and experiment 2 (7288 kg ha⁻¹). The highest observed biomasses of experiment 1 and 2 were from L_11 (7461 kg ha⁻¹) and L_25 (7735 kg ha⁻¹) respectively. The simulation of biomass in experiment 1 showed a higher agreement than experiment 2. Biomass simulations reported that the accession L_1 (N-S 0.85, RMSE 950 kg ha⁻¹) is the best in simulating biomass than the other accessions in the fine-tuned model while L_11 (N-S 0.74, RMSE 1240 kg ha⁻¹) is the poorest. According to a non-parametric t-test, observed and simulated biomasses were not significantly different ($p > 0.05$) in all the accessions.

Grain yield

Model description

In the APSIM millet model, the partitioning of biomass among plant parts is different in growth stages. Only stems and flowers grow between flag leaf and start of grain filling stages. A 19% of dry matter production is allocated to flowers and 81% to stems during these stages. Biomass is partitioned to grains between start of grain filling and maturity stages. The number of grains and grain growth rate determines the grain demand for carbohydrate. In APSIM millet, the number of grains is a function of the dry matter accumulation rate between flag leaf and start of grain filling stages. Temperature and drought stress limit grain growth rate and it is a genotype specific parameter (van Oosterom et al. 2002).

Experimental results

APSIM simulation results of five Proso millet accessions (L_1, L_11, L_12, L_14 and L_25) are shown in Figure 4.8. Faster yielding and completion of crop cycle was

observed in experiment 1 (dry season) than experiment 2 (wet season). However, observed yields of experiment 1 (ranged from 2685 kg ha⁻¹ in L_14 to 3048 kg ha⁻¹ in L_12) were lower than the experiment 2 (2980 kg ha⁻¹ in L_14 to 3438 kg ha⁻¹ in L_25). Initially observed yield is higher than the simulated yield in both experiments in all the tested accessions. A good fit between observed and simulated yield was recorded in all the accessions and none of them was significantly different ($p > 0.05$) according to the non-parametric t-test.

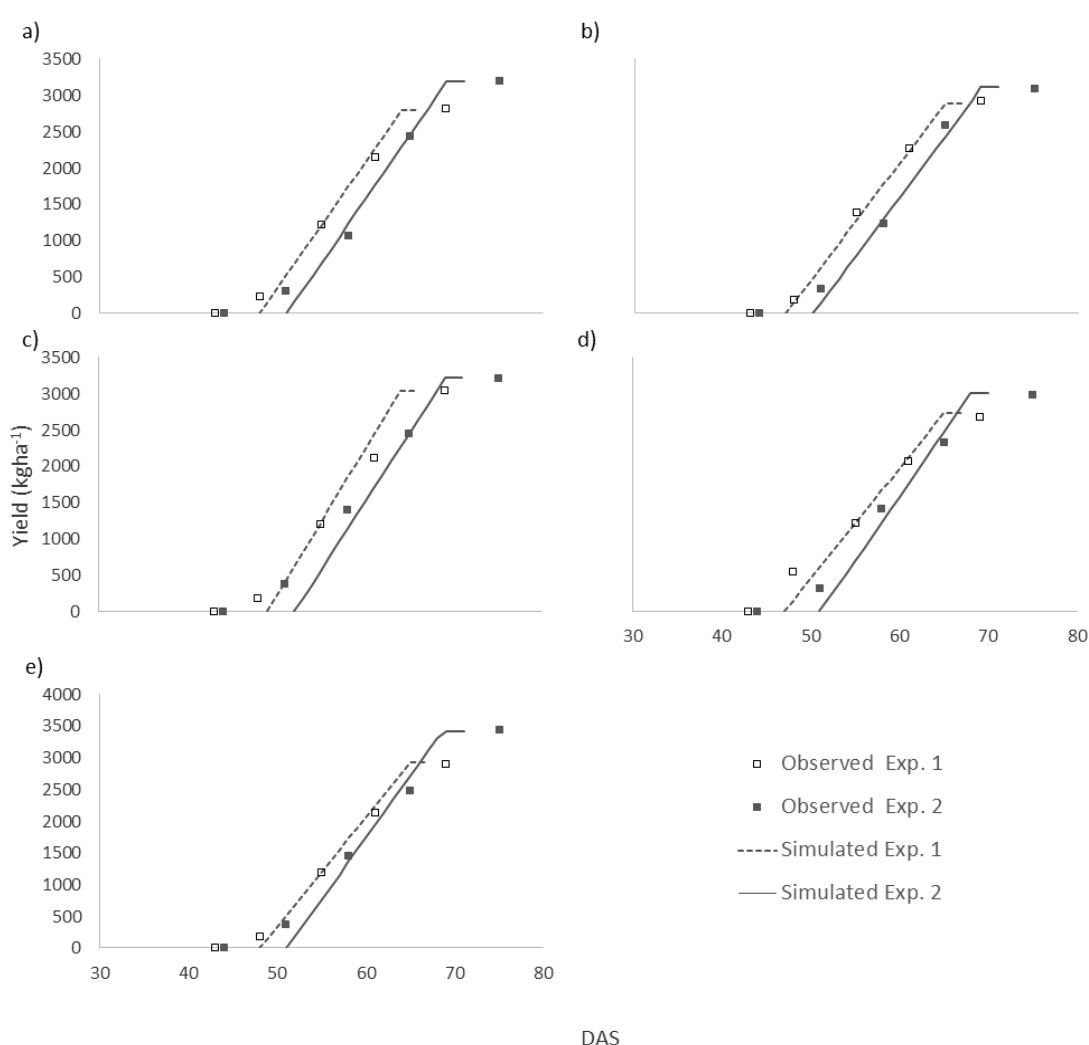


Figure 4.8. Comparison of simulated vs observed grain yield of five Proso millet accessions (a. L_1, b. L_11, c. L_12, d. L_14, e. L_25) from sowing (days after sowing (DAS)) of experiment 1 (2016–dry) and 2 (2017–rainy).

4.4.5. Model validation

Grain yield

The calibrated APSIM millet model was validated by farm field data to ensure that the model predicted yield to match the agronomic reality in Proso millet growing area in Sri Lanka. The simulations were performed for 30 farm fields with 6 fields for each accession. The sensitivity of the calibration of the APSIM millet model to Proso millet accessions was evaluated. It was found that the yields of all the accessions increased after the calibration when compared to the Pearl millet cultivar *hbb67* (selected cultivar for model calibration in APSIM). The yield increment from calibration ranged from 14.5% (RMSE 216.0 kg ha⁻¹ in L_11) to 50.6% (RMSE 581.8 kg ha⁻¹ in L_25).

The slopes of the regression curves of observed and simulated yields of all the accessions (L_1, L_11, L_12, L_14 and L_25) were not significantly ($p > 0.05$) different from zero. The lowest and the highest mean yields of accessions were from L_11 (1056 kg ha⁻¹, SD 256 kg ha⁻¹) and L_25 (1489 kg ha⁻¹, SD 328 kg ha⁻¹) respectively. Similarly, in simulations, L_11 recorded the lowest yield (979 kg ha⁻¹ SD 160 kg ha⁻¹) while the highest yield was from L_25 (1474 kg ha⁻¹ SD 312 kg ha⁻¹). However, both observed and simulated yields and yields from calibration experiments were far below the potential Proso millet yield of 4000 kg ha⁻¹ (Department of Agriculture Sri Lanka).

The linear regression of observed and simulated yield of the five tested accessions (L_1, L_11, L_12, L_14 and L_25) showed both overestimation and underestimation in different fields (RMSE 279 kg ha⁻¹) (Figure 4.9A). Most of the low yielding fields (less than 1000 kg ha⁻¹) show overestimations while high yielding fields (more than 1600 kg ha⁻¹) show underestimations. In general terms, the Proso millet yield of accessions

collected from farmer fields in Sri Lanka can be fairly explained by APSIM millet model. When considering the smaller variation in simulated yields than in observed, it should be noted that the observed data were originated from the fields where crops were raised under different crop management practices, sowing dates, plant densities (ranged from 61– 601, mean 217, SD 94 plants m⁻²), soil properties and seed sources in low input farming systems and these causes of variation are not simulated. This also was expected as crops in farmers' fields tend to suffer from different stresses such as weeds, attacks from higher pests like elephants, peacocks and wild boars.

The probability exceedance distribution pattern for yield data was not separated according to the median values in both observed and APSIM simulated yields (Figure 4.9B). The yields ranged from 687 kg ha⁻¹ to 1841 kg ha⁻¹ in observed fields. In APSIM simulated fields, it ranged from 733 kg ha⁻¹ to 1793 kg ha⁻¹. The probability distributions at lower and higher yields were almost similar while a higher probability distribution was recorded in observed fields in the range of 1134 kg ha⁻¹ to 1400 kg ha⁻¹.

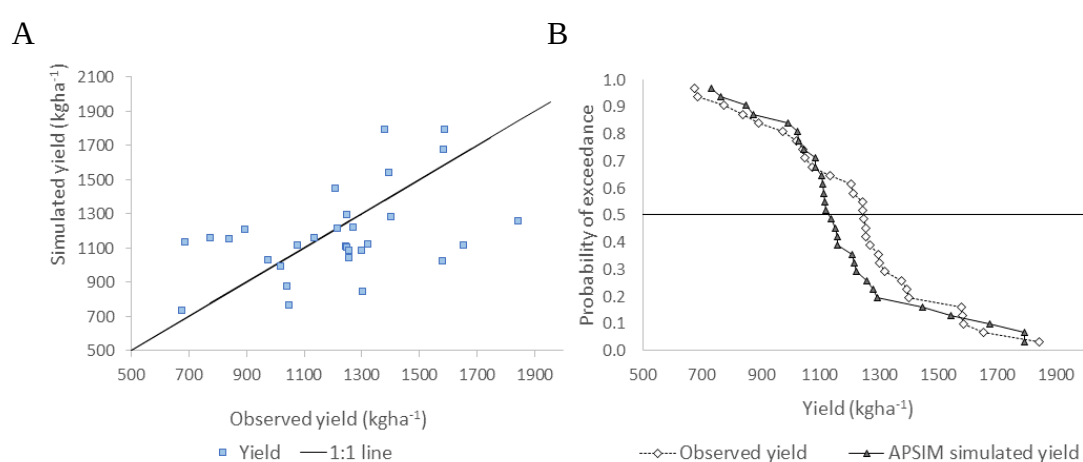


Figure 4.9 A) Comparison of observed and simulated yields and B) the probability of exceedance of five Proso millet accessions for farmer fields in the study area in Sri Lanka during 2015 growing season (n = 30).

Simulated soil water content and grain yield

Proso millet biomass is a function of plant available water and transpiration efficiency (Equation 4.10). Therefore, APSIM simulated plant available soil water content and evapotranspiration were plotted against DAS to study the variation of soil water in 3 selected accessions under farm field conditions and compared with L_1 under experimental conditions (experiment 2) (Figure 4.10). The accessions from farmers' fields were selected as the field with the highest (L_25) and the lowest (L_11) simulated yields, and the field with a yield close to the mean (L_15) in the study area.

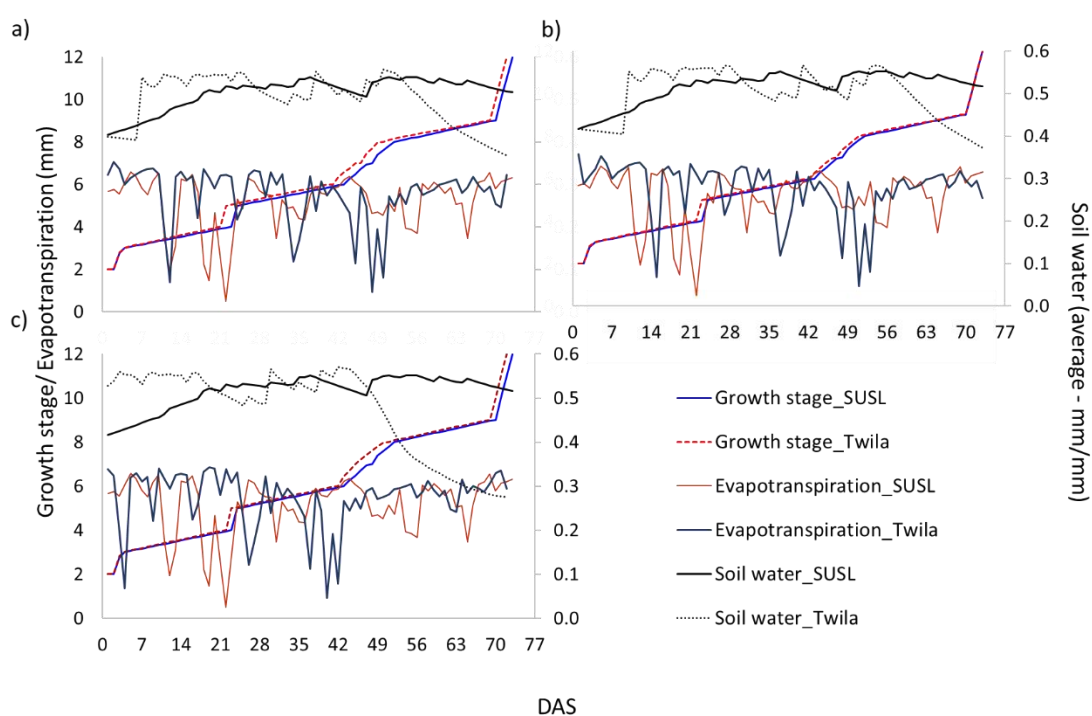


Figure 4.10. Comparison of APSIM simulated growth stage, evapotranspiration and soil water in experiment 2 (L_1) at Sabaragamuwa University of Sri Lanka (SUSL) and farmer fields (a. L_11 b. L_15 and c. L_25) at Thanamalwila (Twila).

It was found that soil water content in farmers' fields was significantly different ($p < 0.05$) from the experimental field in all 3 accessions. In all the accessions, the soil water content in farmers' fields was below the experimental field from the start of grain filling (growth stage 8, 50 – 52 DAS) to harvesting stages (growth stage 12, 72 – 73 DAS). Therefore, low soil water content simulated by the calibrated model can be suggested as the reason for lower yields in farmers' fields. The highest yield was recorded from the accession that was not under water stress from sowing to the end of the juvenile stages (growth stage 4, 22 DAS) when compared with two other accessions (Figure 4.10 c). The water content at farmers' fields was also below that of the experimental fields during the end of the juvenile (21 – 22 DAS) to flag leaf stages (growth stage 6, 41 – 42 DAS) in all the accessions. However, the evapotranspiration values were not significantly different ($p > 0.05$) among farmer fields and the experimental field.

4.5. Discussion

APSIM millet model has been adapted from the Pearl millet crop, which was parameterised in India. Though APSIM has been widely used in Sri Lanka to analyse the various aspects of growth and development, nutrient management and agronomy of rice, this paper presents the first attempt to test APSIM millet model for Proso millet in Sri Lanka. On average, APSIM performed well in simulating the yield of Proso millet in Sri Lanka.

The APSIM millet module can be used for a range of genetically variable varieties/landraces (Holzworth et al. 2014). This model calibration was performed for five genetically unknown Proso millet accessions. Proso millet accessions used in the study originated in different locations across the Dry Zone Sri Lanka. As a result, these accessions can exhibit various site-specific adaptations. The seeds were initially

collected from farmers' fields and farmers use their own seeds for several years after multiplying in a number of generations. They may be from the same landrace or five different landraces and genetic studies are being carried out (not within the scope of this thesis) on the identification of the tested accessions. A good agreement between observed and calibrated LAI, biomass and yield in experiment 1 (dry season) than the experiment 2 (rainy season) suggests the drought favourable characteristics of Proso millet accessions. However, the adaptation of each accession or seed source to a given agroecological environment and intra-landrace variability also can be suggested as the reason for the slight deviation of observed yields of model simulation (Karunaratne et al. 2011).

Proso millet accessions used in the study showed similar phenological characteristics to some commercial varieties (Anderson 1994; Lyon et al. 2008) and landraces (Ghimire et al. 2018) found in the literature. Time to reach 50% flowering varied for accessions both within the country and among different countries (Reddy et al. 2007). Average days to 50% flowering among two accessions in Sri Lanka out of 842 accessions conserved at ICRISAT ranged from 43–47 days. The recorded 43–46 days for flowering was almost similar to the numbers recorded by Reddy et al. (2007).

In both experiment 1 and 2, the simulated LAI values were mostly higher than the observed values (except few data points) while none of the accessions in both experiments reached the mLAI compared to the simulated values. As mentioned in the Equation 4.5, the leaf area of millet can be described by a bell-shaped function on which the position of the largest leaf (X_0), area of the largest leaf (Y_0), breadth (a) and skewness (b) of the leaf area profile determines the area of leaves (van Oosterom et al. 2001a). Further, plant density has a minor effect on X_0 but a major effect on the Y_0 (van

Oosterom et al. 2001a). The extinction coefficient (k) used to calculate light interception is also a function of row spacing (van Oosterom et al. 2001b).

The maximum plant density on which the LAI in APSIM millet model was tested was 12 plants m^{-2} , therefore, to study the impact of spacing on LAI beyond the above mentioned plant density, further modifications to the model are needed. More data on the individual leaf positions and areas (leaf area profiles) and light interception are needed to adjust the sensitivity of factors affecting leaf area to the density beyond 12 plants m^{-2} , therefore, the coefficients related to LAI could not be adjusted for the observed values. In APSIM millet, the increment of plant density decreases the Y_0 (up to the 12 plants m^{-2}) therefore, reduce the LAI. It is also evident from the results (Figure 4.6) that the impact of density is negligible in early growth stages but start to increase at stem elongation (van Oosterom et al. 2001a).

The other negative impact of plant density is shading that can be happened due to the increased LAI of upper leaves that will increase interplant competition leads to tiller death (van Oosterom et al. 2001b). Death of tillers reduce the total biomass of the millet plant and can be the reason for low observed biomass than the simulated values in both experiment 1 and 2. The productivity of tillers is considered as low in simulations, therefore the impact of tiller death on yield is low (van Oosterom et al. 2001b). But in contrast to LAI and biomass, the reduction of yield can be adjusted by the number of grains per panicle (van Oosterom et al. 2002) suggesting a good fit in the yield than the LAI and the biomass.

Consistent overestimation of biomass was observed at the reproductive stage (Figure 4.7). Biomass accumulation is a function of RUE (equation 4.11), therefore, incorrect RUE values lead to inaccurate simulations. The RUE originally quantified by Van

Oosterom et al. (2002) for Pearl millet was used in the model as, 0 in stage 1,2, 11 and 12, 2.17 g/MJ in stages 3-7 and 1.6 g/MJ in stages 8-10. Due to the lack of data on RUE of Proso millet, RUE value of Sorghum (3.2 g/MJ photosynthetically active radiation) which is comparatively higher was used in previous modelling attempts of Proso millet (Saseendran et al. 2009). Therefore, the values for Pearl millet in the existing model (as mentioned above) were used in the simulation in this study. However, it was reported that the total RUE of Proso millet (1.43 g/MJ) was lower than the Pearl millet (1.83 g/MJ) (Kamkar et al. 2005). The RUE of the accessions collected from farmers' fields could be lower than that for Proso millet (Kamkar et al. 2005) and Pearl millet (Van Oosterom et al. 2002), therefore, further overestimation from the calibrated model can be expected. Another important parameter that needs crop-specific data is the canopy extinction coefficient (k). Similar to the RUE, the value defined for Pearl millet was used due to the unavailability of data on k of Proso millet, and can be suggested as another reason for the overestimation of the model. Other than that, radiation interception (Equation 4.11) is high due to the higher LAI which was overestimated at the vegetative stage up to the maximum LAI around 40 DAS (Figure 4.6). Therefore, further calibration of the model for LAI (Equation 4.5) using accession specific data is needed as described previously.

The five tested Proso millet lines (L_1, L_11, L_12, L_14 and L_25) showed lesser variation between accessions with regards to phenology, LAI, biomass and yield in experimental fields that were grown under no water and nutrient stress. But in observed fields and simulations, their yield performances are rather different. Calibration experiments and simulations in the study were undertaken with the assumption that the crop is fully irrigated and not water stressed. But farmers cultivate Proso millet as rainfed crops and experience dry spells during the lifespan. Different sowing dates, land

preparation techniques, seed rates and plant densities can be suggested as the main reasons for the deviations of yield obtained from model simulations compared to observed values. Also, it was observed that some fields were infested with weeds that are likely to negatively affect the yield. The farmer survey revealed that farmers used high plant density as an adaptation technique to recover the damages from excess rainfall and animals and to control weeds (Chapter 2). Therefore, further modelling approaches are needed to study the effect of plant densities on productivity and water use efficiency of Proso millet in the drier parts of Sri Lanka. The unavailability of precise published information on past crop production data hindered the further validation of the model.

Even the plant density is highly variable among farmers' fields (Chapter 2), a lower plant density (20 plants m⁻²) was used in model validation of yield because the APSIM millet was not parameterised for higher plant densities. Previous APSIM simulations to study the effect of plant density on maize revealed that increment of plant density significantly ($p < 0.05$) decreased grain yield and water use efficiency (WUE) (Ren et al. 2016). A positive correlation between evapotranspiration and yield was found for maize and slopes of the equation increased with the increased plant density until reach a plateau suggesting that farmers do not get much benefit with the higher density. It was found that the lower grain weight ($p < 0.10$) was compensated by increased grain number that was associated with prolific tillering in pearl millet (van Oosterom et al. 2002). The optimum density of plants is site-specific and often environment-dependent (Ren et al. 2016). Therefore, common plant densities do not work better for all the fields and they need to be simulated with different densities.

No attempt has been made here to study the effects of differences in the Proso millet plant density in the experimental and farmer fields in Sri Lanka. Therefore, detailed field experiments with different plant densities are needed to understand the effect of plant density on the yield.

4.6. Conclusions

In this chapter, the APSIM millet model was calibrated for five Proso millet accessions (named as L_1, L_11, L_12, L_14 and L_25) collected from Dry Zone Sri Lanka. Two years of field experimental data were used to calibrate the model and data from farmers' fields were used to validate it. Crop phenology, leaf area index, biomass and yield recorded a good agreement between observed and simulated values suggesting a good calibration of genetic coefficients for the millet module of APSIM. Simulation of grain yield is satisfactory but needs further improvement to capture the higher plant density and accession specific characteristics in the growing region. The most probable reason for the discrepancies of observed values from the simulated data is the variability of high plant densities that cannot be captured by the model. The calibrated and validated model can be used to study the growth, development and agronomy of Proso millet. The model will be used in Chapter 5 to study the climate sensitivity and yield projections of Proso millet in Sri Lanka. Identification of knowledge gaps for precise Proso millet modelling in tropical environments was initiated by this calibration exercise.

4.7. Chapter summary

- The phenology, leaf shape factor, leaf area index, above ground biomass and yield of five Proso millet accessions originated from farmers' fields in the Dry of Zone Sri Lanka were studied.
- APSIM millet model was calibrated for selected five Proso millet accessions using experimental data.
- The calibrated model was validated using farmers' field data (Chapter 2).
- The calibrated and validated model will be used to study the climate sensitivity and yield forecasting of Proso millet in mid-21st century (Chapter 5).

Chapter 5

Proso millet production under future climate scenarios (2040–2069) in Dry Zone Sri Lanka

5.1. Introduction

Agricultural and natural ecosystems are affected by the changes in climate. Climate change affects regional temperature, rainfall and evaporation patterns and entire meteorological, hydrological, ecological and agricultural relationships (Rosenzweig 2011). The IPCC (2014) warns that climate change will impose pressure in the Asian region on water availability due to increased monsoon-related interannual rainfall variability, rainfall extremes, intensity and duration of drought. Drought is the main limiting factor for crop production (Seghatoleslami et al. 2008) and identified as a challenge to agriculture in most of the developing countries (Ceccarelli and Grando 1996). Climate variability is one of the most significant reasons for year to year yield variation even under high technology (Kang et al. 2009).

There is ample evidence to suggest that Sri Lanka is vulnerable to climate change (Zoyza and Inoue 2014; Zubair et al. 2015). The vast majority of farmers and consumers in the country will be adversely affected and cultivation of several crops will be at risk due to the limitation of water (Zubair et al. 2015). Sri Lanka also ranked 2nd in the Climate Risk Index (CRI) 2019 released by ‘Germanwatch’, that analyses the extent to which countries have been affected by climate related losses such as storms, floods, heat waves and etc (Eckstein et al. 2019).

Tropical yields of key crops like rice and maize are expected to decline as the climate warms this century (Lobell and Field 2007; Karunaratne et al. 2015; Karunaratne and

Wheeler 2015; Zubair et al. 2015). Unfavourable weather conditions have a direct impact on the agricultural sector in Sri Lanka (Central bank Sri Lanka 2017). Due to the changes in the monsoonal pattern in the country, it is predicted that paddy yield will be declined by 20–30% in the next 2–3 decades (Baba 2010). The failure of South West and North East monsoons created severe drought conditions that lasted around 9 months in the year 2017 and reduced the production of paddy, coconut, sugarcane and vegetables (Central bank Sri Lanka 2017). Due to the drought condition, the production (20.0%) and total extent of cultivation (24.5%) of most of the field crops such as red onion, big onion and chillies decreased, except sorghum, Proso millet and Soya beans (Central bank Sri Lanka 2017). The increment of the extent of low water intensive crops such as Soya beans increased the production growth of 80.8% (Central bank Sri Lanka 2017).

Therefore, evaluation of the sensitivity of different crops to the change of climate and adaptation strategies to minimise climate change impacts in Sri Lanka are essential. It is worth studying other crops that would be more resilient to climate variability like Proso millet. It is an underutilised minor millet that is believed to have drought and stress tolerant characteristics (section 2.2 in Chapter 2). Proso millet is cultivated under harsh environmental conditions in Sri Lanka where other crops (paddy, vegetables, maize and groundnuts) fail in the dry season, and the climate characteristics of the study area are previously described (Chapter 3).

With the substantial uncertainty in climate change projections (Hawkins and Sutton 2009), it is important to study the resilience of drought tolerant underutilised minor millets such as Proso millet. Therefore, the objectives of the Chapter 5 are (i) to predict the future climate of the Proso millet growing area in Sri Lanka using data from 20 general circulation models under different emission scenarios, (ii) to evaluate the

sensitivity of Proso millet production to climate variability by an established coordinated crop-climate modelling approach using calibrated and validated APSIM millet model (Chapter 4) and (iii) to project yields of Proso millet under future climate scenarios (2040–2069) in the growing regions of Sri Lanka.

Chapter 5 is structured as follows. Following the introduction (section 5.1), the next section reviews the literature on climate change and future climate projections in Sri Lanka (section 5.2). The Chapter describes methodology (section 5.3) and results of the future (2040–2069) climate of Proso millet growing area in Sri Lanka, the sensitivity of Proso millet production to climate variability and Proso millet yield projections (section 5.4). Section 5.5 is the discussion and section 5.6 concludes Chapter 5.

5.2. Climate change and crop production in Sri Lanka

This section reviews the literature on climate change and future climate of Sri Lanka and studies on the climate and crop production in the country.

5.2.1. Observed climate change in Sri Lanka

Sri Lanka does not emit a considerable amount of greenhouse gasses (GHGs) to contribute to global warming (Yamane 2009; Baba 2010). However, this does not mean that Sri Lanka is not vulnerable to climate change as rainfall and temperature, the two most important climatic factors for crop production show changes in Sri Lanka when compared with the past data (Zoysa and Inoue 2014; Esham et al. 2017). However, available climate change records on Sri Lanka show contradictory results.

The temperature in Sri Lanka shows a warming trend. The maximum and minimum temperatures of Sri Lanka have increased by an average of 0.026 °C and 0.017 °C per year respectively during the period of 1960–2001 suggesting the heating of daytime

temperature is faster than the night time temperature (Zubair et al. 2005). The country's mean air temperature has increased by 0.016 °C per year for the 1961–1990 period (Chandrapala 1996). Long term temperature analysis has shown that the warming rate in most of the locations in Sri Lanka exceeded the global mean warming rate (0.85 °C over the period 1880 to 2012 – IPCC 2014) during 1906 to 2005 period (De Costa 2008).

For precipitation, there is no coherent increase or decrease of rainfall in Wet or Dry Zones, but Up Country (central part of the country with elevation >900 m – Jayawardene and Weerasena 2001) showed a declining trend of total annual rainfall over 1869–1980 period in Sri Lanka (Jayawardene et al. 2005). Impact of changing rainfall on the agroecological zones of the country (1971–2000) was analysed using the data from 147 meteorological stations and found that a major part of Wet zone showed a decreasing trend of rainfall, the Intermediate Zone showed both increasing and decreasing trends equally and nearly two-third of stations in Dry Zone showed increasing trend (Muthuwaththa and Liyanage 2013). Total annual rainfall amount showed an increasing trend in the Proso millet growing region in Sri Lanka (Chapter 3). Rainfall reduction at low elevation was higher than the high altitudes of the country (Ampitiyawatta and Guo 2009). In general, the increment of temperature was recorded in Sri Lanka while rainfall showed both positive and negative trends in different parts of the country.

5.2.2. Climate change projections for Sri Lanka

Studies on the future climate scenarios for Sri Lanka and the impact of climate change on agriculture are scarce (Eriyagama and Smakhtin 2010). In terms of temperature change, an increment of 1.5 to 2.8 °C in *Yala* season and 1.1 to 2.4 °C in *Maha* season

is expected under mid-century (2040–2070) climate projections of 20 GCMs (RCP8.5) in rice growing areas in North Western Province of Intermediate Zone of Sri Lanka (Zubair et al. 2015). The increment of temperature by 0.5 °C in 2010–2039 and 2–3 °C in 2070–2099 is expected for Walawe basin in the Southern part of Sri Lanka (Jayatillake and Droogers 2004). A 2 – 3 °C temperature increment per 200 years (1901–2100) for RCP4.5 and 3 – 4 °C per 200 years for RCP8.5 is predicted over Sri Lanka using 6 CMIP5 models (Pattnayak et al. 2017). Temperature increment by 0.14 °C (2011–2040 period), 0.91 °C (2041–2070 period) and 1.24 °C (2071–2099 period) was expected for Colombo using regression-based statistical downscaling model (SDSM) under RCP4.5 compared to 1961–1990 period (Dorji et al. 2017).

For precipitation, an increment of average rainfall up to 9.5 mm per day is expected for *Maha* (current average of 6 mm per day) while increment (up to 5.5 mm per day) and reduction (up to 2.5 mm per day) compared to the average of 3.5 mm per day was expected for *Yala* season in Intermediate Zone (Zubair et al. 2015). The mean annual rainfall is expected to increase by 14% and 5% for 2015 under A2 and B2 SRES scenarios respectively, compared to the baseline period of 1961–1990 (De Silva et al. 2007). It is expected that rainfall increment of 0.7% (2011–2040 period), 10% (2041–2070 period) and 13% (2071–2099 period) was projected for Colombo compared to the baseline of 1961–1990 period (Dorji et al. 2017). A higher temporal and spatial variation of rainfall are expected by the end of the century in Sri Lanka (Esham et al. 2017).

As a summary for section 5.2.2, all the studies project warming in the future, but for rainfall, both increment and reduction are expected in different parts of the country.

5.2.3. Impact of climatic on crop yield in Sri Lanka

Different approaches have been used to study the impact of climate change on crop yield in Sri Lanka (Table 5.1). Research attention was given for major crops such as paddy (De Costa et al. 2003; De Silva et al. 2007; Dharmarathna et al. 2014; Zubair et al. 2015), maize (Karunaratne and Wheeler 2015; Karunaratne and Wheeler 2016) and plantation crops (Wijeratne et al. 2007; Peiris et al. 2008). However, the yield forecasting of underutilised crops, that have a potential for future agriculture under climate change (Padulosi et al. 2011) have not been documented under Sri Lankan conditions. Further, the sensitivity of crop yields to the combination of changes in carbon dioxide, temperature and rainfall were not studied previously.

Climate resilience and the behaviour of Proso millet in the future climate in the phase of climate change received lesser research attention in both Sri Lankan level and globally. However, environmental parameters that may have an influence on Proso millet yield (evaporation, water use, plant available water at planting, rainfall during different weeks of the cultivation, temperature and wind) of the Central Great Plains were studied (Nielsen and Vigil 2017).

Table 5.1 Summary of previous studies used to assess the impact of climate parameters on crop yield in Sri Lanka.

Reference	Crop	Research Approach	Key findings
De Costa et al. 2003	Paddy	Linear relationship – to study the response of growth and yield of rice (<i>Oryza sativa</i>) to elevated atmospheric carbon dioxide (570 $\mu\text{mol/mol}$) in the Subhumid Zone of Sri Lanka.	Rice yield increased by 24% (<i>Maha</i> January – March 2011) and 39% (<i>Yala</i> May – August 2011) at elevated CO_2 compared to the ambient conditions.
De Silva et al. 2007	Paddy	Impact of climate change on rice production using HadCM3 model under SRES scenarios for 2100.	Average paddy irrigation requirement for Sri Lanka increased by 23 (A2) and 13% (B2).
Wijeratne et al. 2007	Tea	Author developed model used to study the response of tea to future climate (2050) using 6 GCMs.	The increment of ambient CO_2 concentration (370 ppm) to 600 ppm increased tea yield by 33 – 37%.
Peiris et al. 2008	Coconut	Development of a regression model to forecast coconut production using climatic variables (rainfall, minimum and maximum temperature).	Annual coconut production can be predicted for 15 months in advance from the observed rainfall.
Dharmarathna et al. 2014	Paddy	Evaluate the effect of planting date on rice yield for future yield up to the year 2090 using DSSAT 4.5.	Rice yield is sensitive to the planting date. The yield during the <i>Yala</i> season increased compared to the baseline condition when planted 1 month earlier.

Karunaratne and Wheeler 2015	Maize	Linear regression models fitted to identify the correlation between observed temperature and rainfall with maize yield.	The increment of seasonal mean temperature by 1°C decreased maize yield by 5% from 1990 to 2010 period. Rainfall had a positive significant ($p < 0.10$) correlation with maize yield in Moneragala (during the dry season) and Hambanthota (during the wet season) districts.
Zubair et al. 2015	Paddy	Yield prediction for mid-century for 5 GCMs (RCP8.5) using APSIM-ORYZA and DSSAT-CERES models.	Paddy yield reduced by 27 – 41% (DSSAT) and 2% (APSIM) during the <i>Yala</i> season compared to the baseline period (1980–2010).
Karunaratne and Wheeler 2016	Maize	GLAM—the general large-area model for annual crops was used to simulate the yield for mid-century (RCP8.5) for 5 GCMs.	A yield reduction (up to 18% in the wet season and up to 26% in the dry season) was predicted by GCMs.

As a summary for the Section 5.2, crop and climate modelling applications are not novel in Sri Lanka, however very few attempts were made to study the future climate and behaviour of crops in the country using crop-climate modelling approach. Impact of future climate on Proso millet production and the yield projections were not documented previously. Therefore, following methodologies (section 5.3) were used to study the future climate of Proso millet growing area in Sri Lanka, the sensitivity of Proso millet production to climate variability and yield forecasting for mid-21st century.

5.3. Methodology

5.3.1. Geographic location

The suitability of five Proso millet accessions, L_1, L_11, L_12, L_14 and L_25 (described in Chapter 4), were evaluated for Proso millet growing region (6.428°N, 81.090°E) in Bodagama, Sri Lanka (Chapter 2). Soil (Chapter 2) and rainfall (Chapter 3) characteristics of the study area were previously described.

5.3.2. Baseline (1980–2009) climate data

Yield simulations for baseline period (section 5.3.4), bias correction of future climate (5.3.5) and C3MP analysis (section 5.3.6) were performed using the baseline climate data. Complete observed data set for the 1980–2009 period was not available in the study area. As observed climate data, daily rainfall at Thanamalwila (1989–2009), the closest meteorological station to study area (Chapter 3) along with the daily minimum and maximum temperatures recorded at Sewanagala (1986–2009), which is the only meteorological station with temperature data in Proso millet growing region were used. NASA Modern Era Retrospective-analysis for Research and Applications data (MERRA; Rienecker et al. 2011) that were previously used in Sri Lanka for gap filling in climate change studies (Zubair et al. 2015) were used to fill gaps in rainfall (35.8%

of days), minimum and maximum temperatures (41.2%). None of the stations recorded solar radiation, therefore the data from MERRA were used. However, considering data for 1989–2009, the climatological weekly rainfall (total) and maximum temperature (mean) values of observed and MERRA data were significantly ($p < 0.05$) different among each other while minimum temperature (mean) was not significantly ($p > 0.05$) different according to nonparametric t-test. Weekly distribution of observed (Thanamalwila) and MERRA rainfall data are shown in Figure 5.1. The effect of this gap filling procedure on simulated yields is discussed in section 5.4.1.

5.3.3. Crop model

The calibrated APSIM millet model (version 7.8) was used to simulate the effect of climate variability and change on the yield of five Proso millet accessions (L_1, L_11, L_12, L_14, L_25). The model description, calibration and validation procedures were described in Chapter 4 of the thesis. Soil properties described in Chapter 2 were used in all simulations.

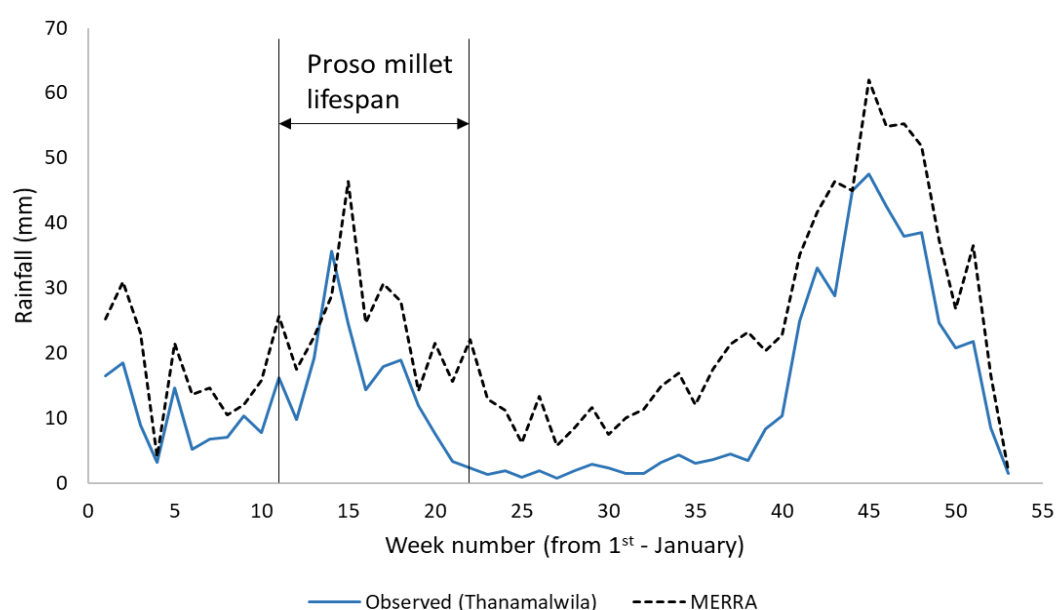


Figure 5.1. Weekly rainfall distribution of observed (Thanamalwila) for 1989–2009 and Nasa MERRA for 1980–2009 period.

Overview of APSIM simulations

Calibrated and validated APSIM millet model (Chapter 4) was used in all the simulations. It was assumed that crop management practices such as planting and fertiliser application dates, amount of fertiliser etc. and soil properties are similar in all the simulations while the only difference was among the climate data. APSIM simulations performed in this chapter are summarised in Table 5.2.

Table 5.2. Summary of APSIM simulations conducted in Chapter 5 of the thesis

Simulation	Purpose	Section of the thesis
Baseline (1980–2009) yield	To study Proso millet yields for baseline (1980–2009) period.	5.3.3 and 5.4.1.
Yield projection (2040–2069)	Proso millet yield projection for 2040–2069 period using 20 GCMs (A–T in Table 5.3).	5.3.4 and 5.4.4
C3MP	To evaluate the sensitivity of Proso millet production to changes in temperature and rainfall according to the C3MP 99 climate sensitivity tests (Appendix 3)	5.3.5. and 5.4.3.

5.3.4. Proso millet simulations for baseline (1980–2009) period

In order to calculate the percentage yield change (section 5.4.4) under future (2040–2069) climates, Proso millet yield during the baseline period was initially simulated. Simulations were performed for the baseline climate data (1980–2009) that were described in section 5.2.2.

5.3.5. Mid-21st century climate and yield projections

The climate and yield projections of the study included 30 growing seasons for the mid-21st century (2040–2069), using downscaled climate model data. The climate scenarios for the study were obtained from 20 General Circulation Models (GCMs) (labelled A–T in Table 5.3) in the Coupled Model Intercomparison Project (CMIP5) archive (Taylor et al. 2012), which were selected as those are available for both RCP4.5 and RCP8.5 in the online data portal (<http://ccafs-climate.org/>) of Consultative Group for International Agricultural Research (CGIAR) Research Program on Climate Change, Agriculture and Food Security (CCAFS).

The CMIP5 utilise four Representative Concentration Pathways (RCPs) to capture the range of greenhouse gas (GHG) concentration and associated radiative forcing. Four RCPs (RCP2.6, RCP 4.5, RCP 6 and RCP 8.5) were defined by their total radiative forcing (the total amount of GHGs emitted by human activities in Wm^{-2}) pathway and level by 2100 (IPCC 2014). Two RCPs were selected for this study as; RCP4.5 represents the medium-lower concentration scenario that is fairly consistent with the current mitigation policies and RCP8.5 represents the most extreme high emission scenarios (IPCC 2014).

The direct use of coarse resolution (100 – 200 km) GCMs is not practical for assessing the agricultural impact of a small location, especially in the tropics (Ramirez-Villegas

and Jarvis 2010). Because climatic and soil conditions vary significantly over small distances increasing model uncertainties and making forecasting models more inaccurate (Ramirez-Villegas and Jarvis 2010). Therefore, daily rainfall, minimum and maximum temperatures and solar radiation data for mid-century (2040–2069) were downscaled, based on the “delta method” (Wilby et al. 2004). The delta method assumes that the relationships between variables of the current (baseline) climate are maintained towards the future and changes in climate are relevant at coarse scales (Ramirez-Villegas and Jarvis 2010). However, these assumptions may not be true in highly heterogenous landscapes where topography cause substantial variations over small distances (Ramirez-Villegas and Jarvis 2010). The delta method is one of the simplest and widely used methods of downscaling climate data (Trzaska and Schnarr 2014) and previously used for future climate studies in Sri Lanka (Zubair et al. 2015). In the delta method, the differences between current and future GCM simulated climate are added to the observed current climate (Hawkins et al. 2013; Navarro-Racines et al. 2015). Downscaling has been done for minimum and maximum temperatures, rainfall and solar radiation separately.

Yield simulations for mid-century (2040–2069) were performed using calibrated and validated APSIM millet model (Chapter 4) for 5 Proso millet accessions (L_1, L_11, L_12, L_14 and L_25 (Chapter 4).

Table 5.3. Description of General Circulation Models (GCMs) used in the study

Symbol	Model	Description/Institute	Resolution of Atmospheric Grid (decimal degrees)
A	BCC-CSM1-1	Beijing Climate Centre, China Meteorological Administration, China	2.7906 x 2.8125
B	BCC_CSM1_1_M	Beijing Climate Centre, China Meteorological Administration	2.7906 x 2.8125
C	BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University, China	2.7906 x 2.8125
D	CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	2.7906 x 2.8125
E	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation and the Queensland Climate Change Centre of Excellence, Australia	1.8653 x 1.875
F	GFDL_CM3	Geophysical Fluid Dynamics Laboratory, USA	2.0 x 2.5
G	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory, USA	2.0225 x 2.0
H	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, USA	2.0225 x 2.0

I	INMCM4.0	Institute for Numerical Mathematics, Russia	1.5 x 2.0
J	IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France	1.8947 x 3.75
K	IPSL-CM5A-MR	Institut Pierre-Simon Laplace, France	1.2676 x 2.5
L	MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies, Japan	2.7906 x 2.8125
M	MIROC_ESM_CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies, Japan	2.7906 x 2.8125
N	MIROC5	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology	1.4008 x 1.40625
O	HadGEM2-CC	Met Office Hadley Centre, UK	1.25 x 1.875
P	HadGEM2-ES	Met Office Hadley Centre, UK	1.25 x 1.875

Q	MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	1.8653 x 1.875
R	MPI-ESM-MR	Max Planck Institute for Meteorology, Germany	1.8653 x 1.875
S	MRI-CGCM3	Meteorological Research Institute, Japan	1.12148 x 1.125
T	NorESM1-M	Norwegian Climate Centre, Norway	1.8947.5

Grid resolutions were adapted from the European Network for Earth System Modelling (<https://portal.enes.org>).

5.3.6. Coordinated Climate-Crop Modelling Project (C3MP)

Being the primary drivers of climate change, it is important to study the sensitivity of crop yields to changes in carbon dioxide concentration ($[CO_2]$), temperature and rainfall (Mcdermid et al. 2015). The Agricultural Model Intercomparison and Improvement Project (AgMIP) developed Coordinated Climate-Crop Modelling Project (C3MP) to study the sensitivity of crop yields to changes in $[CO_2]$, temperature and rainfall by 99 combinations of these variables (Appendix 3). In contrast to climate projections (using GCMs), C3MP analysis is not based on emission scenarios, do not estimate climate or location dependent, but universal to every agricultural land in the world. The C3MP sensitivity tests (Ruane et al. 2014; Mcdermid et al. 2015) are designed to test the combinations of projected temperature, rainfall and carbon dioxide changes at the end of the 21st century, but within a defined range (Table 5.4). The C3MP has extended the climate metric range (Table 5.4) slightly beyond the climate extremes projected by GCMs for the CMIP5 (Ruane et al. 2014).

Table 5.4. Climate metric ranges for C3MP climate sensitivity experiments.

Climate Metric	Lower Bound	Upper Bound
Temperature change	−1 °C	+8 °C
Rainfall change	−50%	+50%
Carbon dioxide concentration	330 ppm	900 ppm

This range covers the majority of cropping areas in the world, although a larger percentage changes to small baseline rainfall amount are expected in some arid regions (Mcdermid et al. 2015). The [CO₂] will be higher than 900 ppm under the RCP8.5 scenario at the end of the century, however, C3MP is focused on 900 ppm as the upper limit. The 99 climate sensitivity tests (Appendix 3) were generated using Latin Hypercube sampling method (Mcdermid et al. 2015) and changes in rainfall and temperature were applied to baseline (1980–2009) daily weather data (Chapter 3).

It was found that the APSIM millet model was not parameterised for the sensitivity to variations in CO₂ concentration by the model developers and it was not possible to add such a parameterization within the time scale of the study. Proso millet is a C₄ plant and the response to CO₂ are lower in C₄ plants than C₃ plants (von Caemmerer and Furbank 2003). Therefore, it was not expected that the reduction of yield due to increased temperature is offset by the increased [CO₂]. Hence, CO₂ was omitted, and the analysis proceeded with varying rainfall and temperature only. The issues and possible outcomes of not including CO₂ variations are discussed later in this chapter (section 5.5). Climate control option of the APSIM model was used to create 99 climate sensitivity tests (Appendix 3) in simulations. Each sensitivity test consisted of 30 years of simulations based on the baseline (1980–2009) daily historical climate data (Chapter

3) and the 99 climate sensitivity analysis resulted in 2970 (99 tests x 30 years) yield simulations per one Proso millet accession.

5.3.7. Data analysis

ANOVA, t-tests and regression analysis were performed using Prism (Version 7.03) while Microsoft Excel and R packages were used for graphing.

5.4. Results

5.4.1. Effect of gap filling on the yield

The 1992–1996 period that did not have any gaps in both rainfall and temperature was selected and compared for climate data and simulated yield (Figure 5.2). The yields were plotted for observed rainfall and temperature (‘Observed T and RF’), observed temperature (rainfall from MERRA – ‘Observed T, MERRA RF’), observed rainfall (temperature from MERRA – ‘MERRA T, Observed RF’) and MERRA data only (‘MERRA T and RF’) (Figure 5.3).

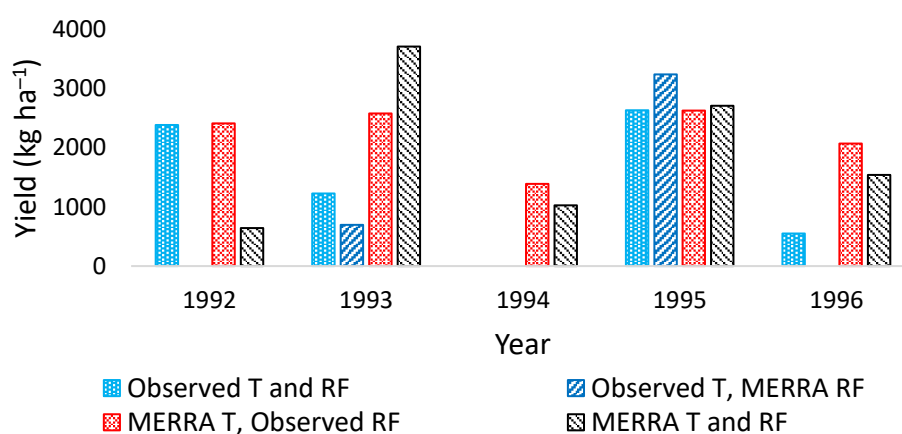


Figure 5.2. Comparison of simulated Proso millet yield for observed rainfall and temperature (Observed T and RF), observed temperature and rainfall by MERRA (Observed T, MERRA RF), MERRA temperature and observed rainfall (MERRA T, Observed RF) and MERRA temperature and rainfall (MERRA T and RF) for 1992–1996 period.

Observed temperature and rainfall data did not record yield for year 1994 while the yield was zero in 1992, 1994 and 1996 for observed temperature and MERRA rainfall data (Figure 5.2). Therefore these 4 failed events were not represented by circles in Figure 5.3. None of the years in two other data sets ('MERRA T, Observed RF' and 'MERRA T and RF') were failed.

The following multiple regression model was developed using seasonal mean minimum and maximum temperatures and rainfall for 1992–1996 period.

$$\text{Yield} = 17267.19 - 364.45 \cdot T_{\text{max}} - 210.12 \cdot T_{\text{min}} + 5.12 \cdot \text{RF}$$

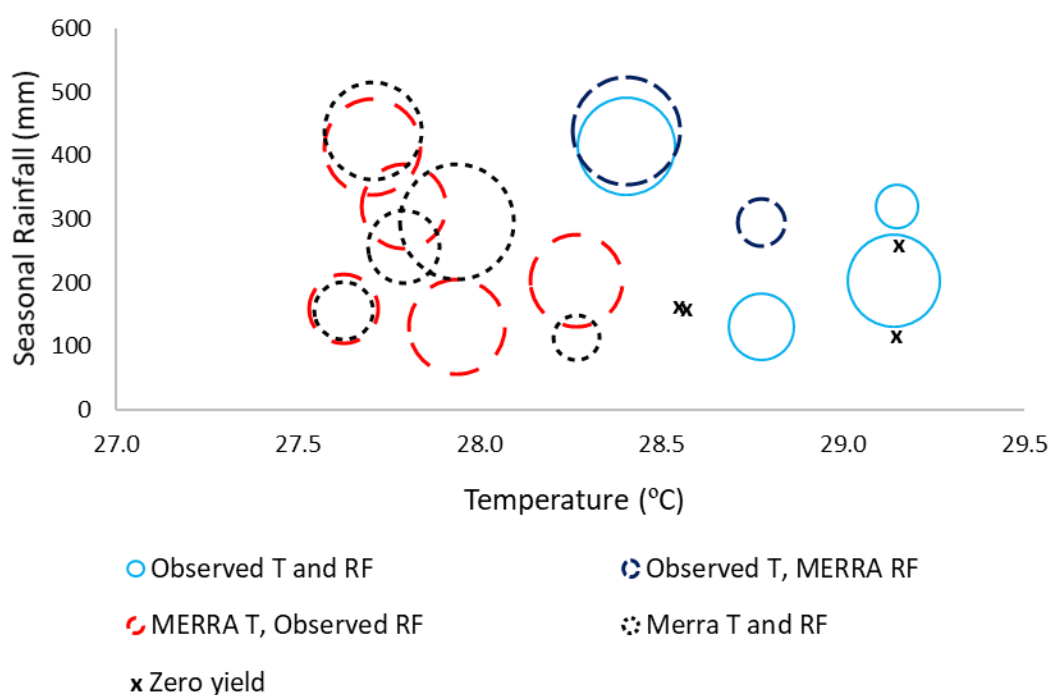


Figure 5.3. Comparison of simulated yield for observed rainfall and temperature (Observed T and RF), observed temperature and rainfall by MERRA (Observed T, MERRA RF), MERRA temperature and observed rainfall (MERRA T, Observed RF) and both temperature and rainfall by MERRA (MERRA T and RF) under different mean temperature and seasonal rainfall during 1992–1996 period. The size of the circle represents the yield in the respective years. Failed years (zero yield) are also marked.

The Tmax and Tmin are seasonal mean maximum and minimum temperatures (°C) while RF is the seasonal mean rainfall (mm). According to the multiple regression, the highest yield reduction was due to the increment of maximum temperature (Tmax) followed by minimum temperature (Tmin). The increment of rainfall by 1 mm increased the yield by 5.12 kg ha⁻¹ for 1992–1996 period.

The yield decreased in observed climate data due to the higher maximum temperature of observed (Tmax 34.2±0.5 °C) compared to MERRA data (Tmax 31.4±0.2 °C). In contrast, according to Tmin, a higher reduction was recorded from MERRA (Tmin 24.3±0.1 °C) than the observed (Tmin 23.4±0.2 °C) climate data. The mean rainfall of observed and MERRA data were 245±119 mm and 252±127 mm. According to the results, a combination of minimum and maximum temperatures and rainfall make yield variation in both observed and gap-filled data. The variation of yield can be different throughout the period (1980–2009) according to the temperatures and rainfall data of the respective year.

5.4.2. Proso millet simulation for baseline (1980–2009) period

Proso millet yield during the baseline period was studied initially in order to calculate percentage yield change for future period (2040–2069). The average yield for the baseline climate period ranged from 1622 kg ha⁻¹ (SD 941 kg ha⁻¹) in L_14 to 1823 kg ha⁻¹ (SD 1036 kg ha⁻¹) in L_25 with the mean of 1707 kg ha⁻¹ for all the accessions. The simulated yields of five different accessions for thirty years were not significantly different ($p > 0.05$) from each other. Out of thirty years, 15 years (50%) showed higher yields than the average while the rest of the years were below the average. The average yield for the baseline period was 31% higher than the observed yield for the 2015 growing season in the area (section 2.4.5). The observed rainfall at Thanamalwila for Proso millet growing season (15th March – 15th June) in the year 2015 (462 mm) was

higher than the multi-modal mean rainfall under RCP4.5 (297 mm) and RCP8.5 (361 mm) (Table 5.5).

Yields were very low in several years. Proso millet production failed in 1994 as it did not produce yields in any of the accessions under observed meteorological data. The average yield for the year 1985 was just 8 kg ha⁻¹ for all the accessions and can be considered as another failed year. In Chapter 3 it was shown that both 1994 and 1985 were considered as years with very late onset of growing season since the onset of the growing season were on 8th September and 5th June respectively. In the year 2001, the onset of the season was 8th April, but observed rainfall data were missed in May. With the use of MERRA data, it was found that the retreat was 30th April (mean retreat of the region 15th May) with the length of 22 days (mean length of the region 52 days). Therefore, the shorter growing season can be suggested as the reason for the failed cultivation in the year 2001. Rainfall amount during mean Proso millet growing period (26th March – 2nd June) for the above three years was low: 158.9, 125.4 and 157.5 mm respectively.

The highest yield of 3718 kg ha⁻¹ was from the year 1982 and it was more than two times higher than the average yield for the 1980–2009 period. In the year 1982, the onset of the season was 3rd March with a length of 101 days and 402.3 mm of rainfall for Proso millet growing period. The onset of 1986 was failed according to the definition (19th October) but received 141 mm rainfall during Proso millet growing period and recorded the second highest yield within 30 years period. Increment of soil water content (described later in this chapter) due to intermittent rains support the crop growth in the year 1986 (Figure 5.6). The relationship between date of onset and rainfall amount during average Proso millet growing period (26th March – 2nd June) with the yield was discussed later in this section.

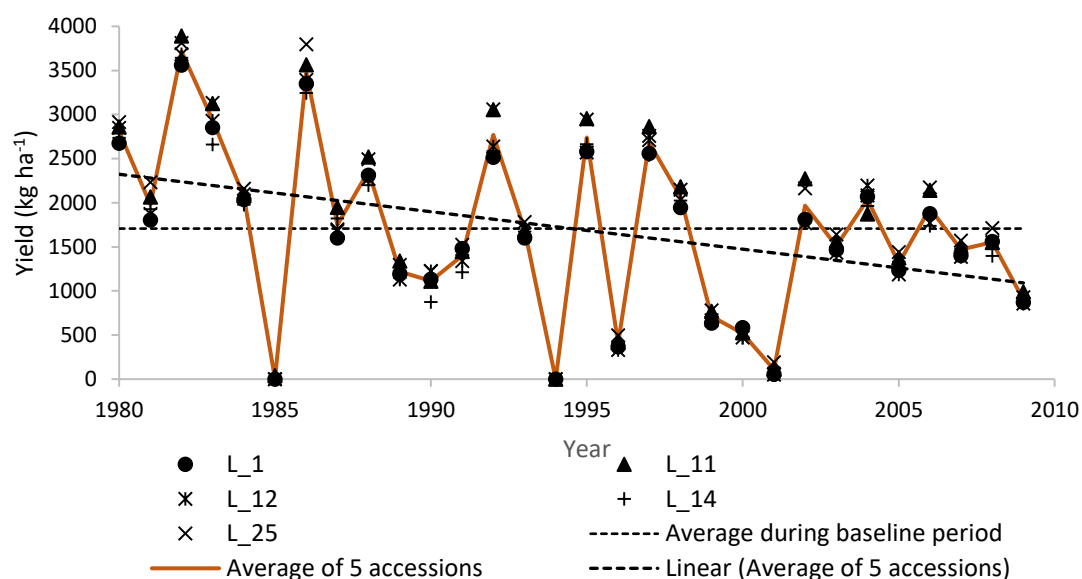


Figure 5.4. Variation of Proso millet yield in five accessions (L_1, L_11, L_12, L_14 and L_25 as symbols) and average yield (solid line) during the baseline (1980–2009) period.

The average yield variation of five accessions showed a negative trend (42.5 kg ha^{-1} per year) throughout the 1980–2009 period and it was significantly different from zero ($p=0.0384$) at 95% probability level. The yield variation of five accessions, an average of all the accessions and its linear trend is shown in Figure 5.4.

It is important to know which environmental factors are driving the year-to-year variation in yields. Because it was shown in Chapter 3 that the rainfall has a clear relationship with Proso millet cultivation in the growing region in Sri Lanka (Figure 3.2 and 3.5). The onset of the season and rainfall amount during Proso millet cropping period in APSIM simulations (26th March – 2nd June) did not show a clear relationship with Proso millet yields ($r = -0.07$ and 0.42 respectively). Therefore, stepwise regression was performed for 17 environmental factors believed to influence Proso millet yield (Appendix 4) based on the available literature (Lyon et al. 2008; Seghatoleslami et al. 2008; Nielsen and Vigil 2017). The method followed by Nielsen

and Vigil (2017) to study the influence of environmental parameters on Proso millet in Great Plains was used to perform the analysis.

The stepwise regression procedure developed the following regression model that has the most influencing environmental factors on Proso millet out of the 17 parameters, using APSIM simulated yield data for 1980–2009 period. It should be noted that the coefficients of the regression model were also developed in the stepwise regression process.

$$\text{Yield} = 689.596 + 52.408 \cdot D_{RF} - 18.067 \cdot T_{\max 34} + 9.548 \cdot RF_6 + 14.386 \cdot RF_7 + 11.391 \cdot RF_5 - 4.449 \cdot RF_2 - 26.521 \cdot T_{\max 32}$$

Where,

Yield= Proso millet grain yield (kg ha⁻¹)

D_{RF} = rainy days (precipitation >0.85 mm) during the cropping period (26th March – 2nd June)

$T_{\max 34}$ = number of days from 01 May to 02 June (flag leaf initiation to end of the crop) with maximum temperature greater than 34 °C

RF_6 = rainfall (mm) from 30 April to 06 May (35 to 41 DAS)

RF_7 = rainfall (mm) from 07 May to 13 May (42 to 48 DAS)

RF_5 = rainfall (mm) from 23 April to 29 April (28 to 34 DAS)

RF_2 = rainfall (mm) from 02 April to 08 April (7 to 13 DAS)

$T_{\max 32}$ = number of days from 01 May to 02 June (flag leaf initiation to end of the crop) with maximum temperature greater than 32 °C

Predicted yields from this model correlated well ($r = 0.91$, $R^2 = 0.8$) with the APSIM simulated yield suggesting that the regression model captured the most important environmental parameters influencing Proso millet yield (Figure 5.5). Therefore, failed

season in a few years (1985 and 1994) and very high yield in some of the years (such as 1982) can be explained by the regression model. But comparatively lower yield was predicted by the regression model (2943 kg ha⁻¹) for the second highest yield (3469 kg ha⁻¹) in the year 1986.

The coefficients generated from the stepwise regression have following meanings; Proso millet yield increased by 52.408 kg ha⁻¹ for increment on one rainy day and 11.391 kg ha⁻¹, 9.548 kg ha⁻¹ and 14.386 kg ha⁻¹ by increment of each mm of rainfall during 23 April to 29 April (5th week), 30 April to 06 May (6th week) and 07 May to 13 May (7th week) respectively. The yield decreased by 18.067 kg ha⁻¹ and 26.521 kg ha⁻¹ when the number of days from 01 May to 02 June with a maximum temperature greater than 34 °C and 32 °C increased by one, respectively. Increment of 1 mm of rainfall from 02 April to 08 April (2nd week) decreased Proso millet yield by 4.449 kg ha⁻¹.

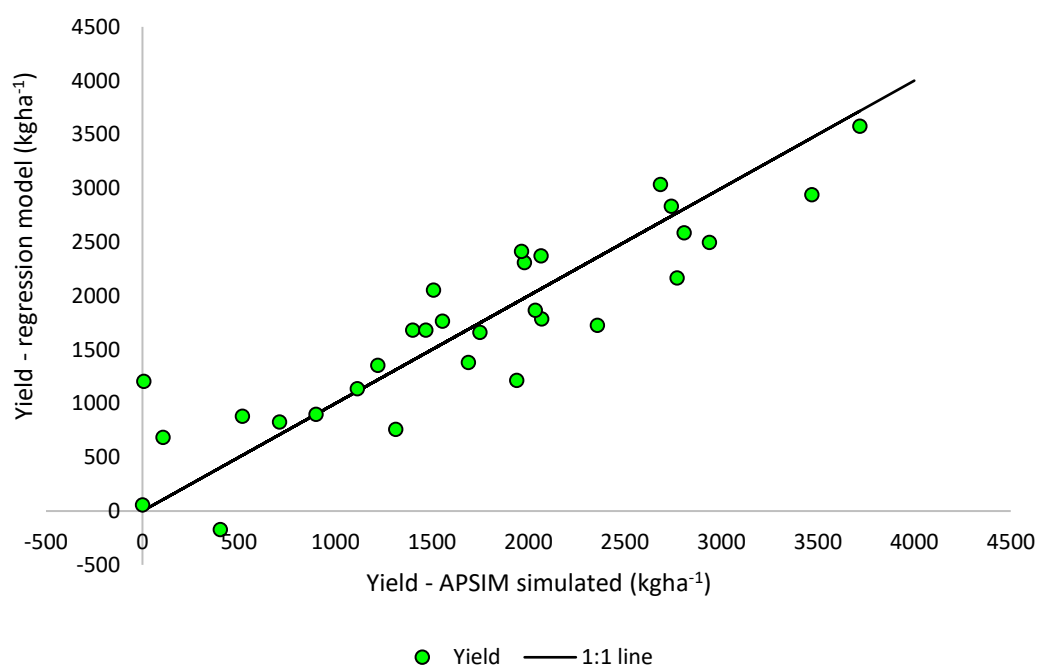


Figure 5.5. Comparison of APSIM simulated and stepwise regression model predicted yields for the baseline period.

It was evident that the failure or high yield during the baseline period (1980–2009) was due to several environmental factors instead of one. Being the most important climate parameter in Dry Zone Sri Lanka, rainfall favours Proso millet while high temperature (above 32 °C) decrease the yield. In rainfall, both the amount and the distribution are important for a successful Proso millet cultivation.

As mentioned in Chapter 4, APSIM simulated yield (and biomass accumulation) of Proso millet plant depends on soil water supply (Equation 4.10) and radiation use efficiency (Equation 4.11). Further, stresses caused by drought cause plant death (Chapter 4). In APSIM simulations, it was found that the reduction of plant available soil water from end of juvenile (growth stage 4) and floral initiation (growth stage 5) stages makes very low yield in the year 1985 and 2001 (Figure 5.6). Proso millet plants died during floral initiation stage in the year 1994 therefore, they did not produce grains. Soil water content in the year 1982 (the highest yield) and year 1986 (the second highest yield) were low in initial stages (emergence to floral initiation) than the average for 30 years period but increased at the end of vegetative stages therefore, a higher yield was recorded. Therefore, the timing of water availability is an important factor that determines Proso millet yield.

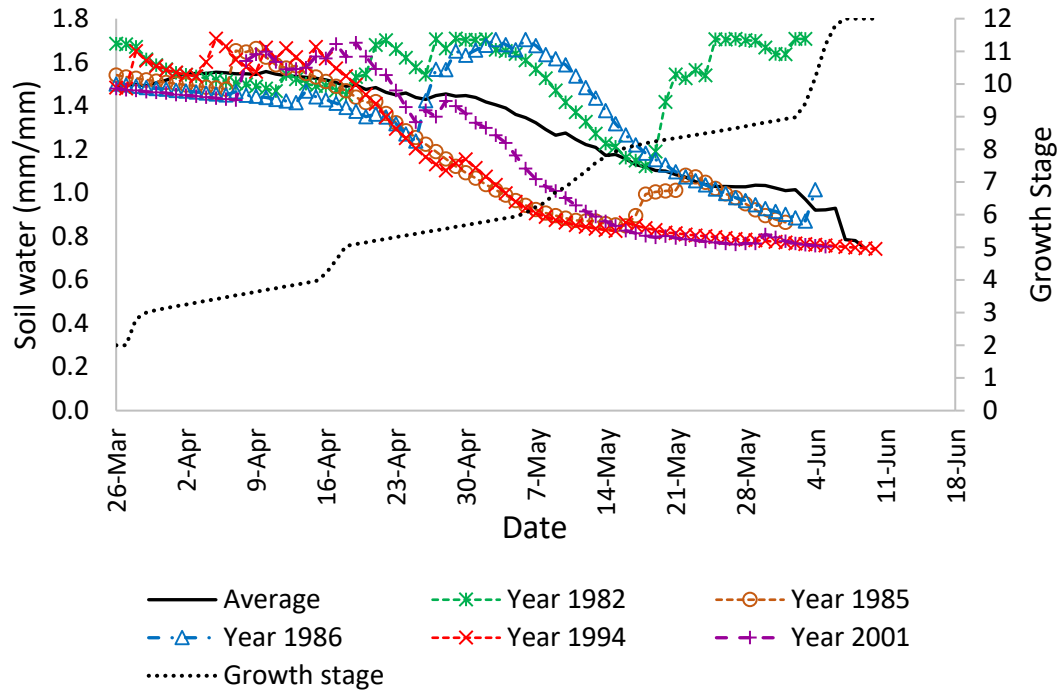


Figure 5.6. Changes in plant available soil water content in selected years (year 1985, 1994 and 2001 as failed years, 1982 – the highest yielding year and 1986 – the second highest yield) with simulated average growth stages. Developmental stages were defined as 1=sowing, 2=germination, 3=emergence, 4=end of juvenile, 5=floral initiation, 6=flag leaf, 7=flowering, 8=start grain fill, 9=end of grain filling, 10=maturity, 11=harvest ripe and 12= harvest (Chapter 4).

5.4.3. Mid-21st century climate of Proso millet growing area

Daily data covering 2040–2069 period was initially used to study Proso millet yields under future climate. The annual and Proso millet growing seasonal (15th March to 15th June) climate during the observed baseline period (1980–2009) and over the mid of the 21st century (2040–2069) for the downscaled 20 GCMs under RCP4.5 and RCP8.5 are summarised in Table 5.5.

The mean maximum temperature (Tmax) and minimum temperature (Tmin) of the baseline period (1980–2009) were 32.1 °C and 23.3 °C respectively. The mean Tmax and Tmin increased in all the GCMs under both RCP4.5 and RCP8.5 scenarios. The mean Tmax increased by 0.6 °C (INM_CM4) to 2.1 °C (GFDL_CM3) in RCP4.5 while

1.0 °C (INMCM4.0) to 2.8 °C (GFDL_CM3) in RCP8.5. The mean Tmax for 2040–2069 period under RCP4.5 and RCP8.5 was 33.3 °C and 34.0 °C respectively.

The mean (Tmean) annual temperature ranged from 28.3 °C (INMCM4.0) to 29.7 °C (GFDL_CM3) under RCP4.5 and 28.7 °C (INMCM4.0) to 30.5 °C (GFDL_CM3) under RCP8.5 scenario. In Proso millet growing season, Tmean ranged from 29.0 °C (INMCM4.0) to 30.5 °C (CSIRO-Mk3-6-0) for RCP4.5 and 29.4 °C (INMCM4.0) to 31.2 °C (GFDL_CM3) for RCP8.5.

The annual and Proso millet growing seasonal rainfall during the baseline period was 1121 mm and 289 mm respectively. Under RCP4.5, seventeen GCMs (85%) showed an increment of annual rainfall while 3 GCMs (15%) exhibited a decrease in annual rainfall compared to the baseline period. The rainfall increment ranged from 0.3% (BCC_CSM1_1) to 45.2% (CSIRO_Mk3_6_0). The annual rainfall decreased by 6.8% (GFDL_ESM2M) to 3.3% (INM_CM4) under RCP4.5.

Proso millet growing seasonal rainfall increased in 13 GCMs (65%) and decreased in 7 GCMs (35%) for RCP4.5 emission scenario. Proso millet growing seasonal rainfall increased from 0.3% (HadGEM2_CC) to 54% (GFDL_ESM2G). The rainfall amount during the growing season decreased by 23.2% (CSIRO_Mk3_6_0) to 2.4% (INM_CM4). Comparatively higher variation was observed in the Proso millet growing seasonal rainfall than the annual rainfall.

Table 5.5. The annual mean maximum and minimum temperatures, annual and growing seasonal (15th March – 15th June) rainfall for the baseline period (1980–2009) and in mid of the 21st century (2040–2069) for 20 general circulation models under the RCP4.5 and RCP8.5 scenarios in Bodagama, Sri Lanka.

Model	RCP4.5				RCP8.5			
	Mean	Mean	Total annual	Seasonal	Mean	Mean	Total annual	Seasonal
	Tmax (°C)	Tmin (°C)	rainfall (mm)	rainfall (mm)	Tmax (°C)	Tmin (°C)	rainfall (mm)	rainfall (mm)
Baseline	32.1	23.3	1121	289				
BCC-CSM1-1 (A)	33.1	24.4	1124	321	33.4	24.7	1360	338
BCC_CSM1_1_M (B)	33.2	24.3	1065	249	33.5	24.7	1107	253
BNU-ESM (C)	33.2	24.5	1249	298	33.7	25.0	1331	344
CanESM2 (D)	33.7	24.8	1264	300	34.5	25.6	1661	445
CSIRO-Mk3-6-0 (E)	33.3	25.0	1628	222	34.2	25.4	1291	313
GFDL_CM3 (F)	34.2	25.3	1300	333	34.8	26.1	1908	1088
GFDL-ESM2G (G)	33.2	24.3	1247	445	33.7	25.0	1050	257

GFDL-ESM2M (H)	33.4	24.4	1045	228	33.8	25.0	995	198
INMCM4.0 (I)	32.6	23.8	1084	282	33.0	24.3	1046	285
IPSL-CM5A-LR (J)	33.7	24.9	1383	308	34.6	25.5	935	169
IPSL-CM5A-MR (K)	33.5	24.9	1331	319	34.3	25.5	1800	279
MIROC-ESM (L)	33.2	24.7	1244	274	34.0	25.2	1265	305
MIROC_ESM_CHEM (M)	33.0	24.7	1226	303	34.2	25.4	1346	355
MIROC5 (N)	33.3	24.5	1225	296	33.9	25.1	1896	491
HadGEM2-CC (O)	33.4	24.8	1169	290	34.1	25.3	1284	358
HadGEM2-ES (P)	33.6	25.0	1222	303	34.2	25.4	1200	377
MPI-ESM-LR (Q)	33.4	24.6	1239	254	34.1	25.2	1129	268
MPI-ESM-MR (R)	33.3	24.7	1438	334	34.1	25.2	1160	287
MRI-CGCM3 (S)	33.1	24.3	1213	275	33.6	24.7	1235	462
NorESM1-M (T)	33.1	24.3	1227	314	33.7	24.9	1798	349
Multi-model mean	33.3	24.6	1246	297	34.0	25.2	1340	361

Under RCP8.5, the annual rainfall increased in 15 GCMs (ranged from 0.8% in MPI-ESM-LR to 70.3% in GFDL_CM3). The IPSL-CM5A-LR recorded the highest annual rainfall reduction (16.6%) for RCP8.5. Rainfall during Proso millet growing season increased in 12 GCMs (60%) and 8 GCMs (40%) projected rainfall reduction.

According to GFDL_CM3, it is expected that rainfall during Proso millet growing season for the 2040–2069 period will increase up to 1088 mm (277% compared to the baseline) while the average of 19 other GCMs was 323 mm, therefore GFDL_CM3 was identified as an outlier under RCP8.5 scenario for Proso millet growing seasonal rainfall projection. The GFDL_CM3 recorded both overestimation and underestimation than the multimodal mean and baseline period while the extreme rainfall increment was projected for April only (Figure 5.7). The reduction of monthly rainfall than the baseline (5.6 to 42.4%) and the average of other 19 GCMs (4.8 to 62.1%) during 7 months (January to March and August to November) reduced the annual rainfall increment of GFDL_CM3 model to 70.3%. However, annual and Proso millet growing seasonal rainfall of GFDL_CM3 under RCP4.5 did not show extreme values (Table 5.5).

The increment of growing seasonal rainfall of GFDL_CM3 was followed by MIROC5 with 70.2% increment. The rainfall during Proso millet growing season reduced from 0.6% (MPI-ESM-MR) to 41.3% (IPSL-CM5A-LR). It was recorded that 50% of GCMs under RCP4.5 and 40% of GCMs under RCP8.5 were below the lower limit (300 mm) of rainfall where Proso millet gives a satisfactory yield (Changmei and Dorothy 2014). Monthly distribution pattern of rainfall follows a bi-modal distribution (Figure 5.7) as similar to Figure 3.2A. Comparatively higher variation was recorded for both annual (CV – coefficient of variation 0.11 and 0.23) and Proso millet growing seasonal (CV 0.16 and 0.52) rainfall under RCP4.5 than the RCP8.5 scenario respectively.

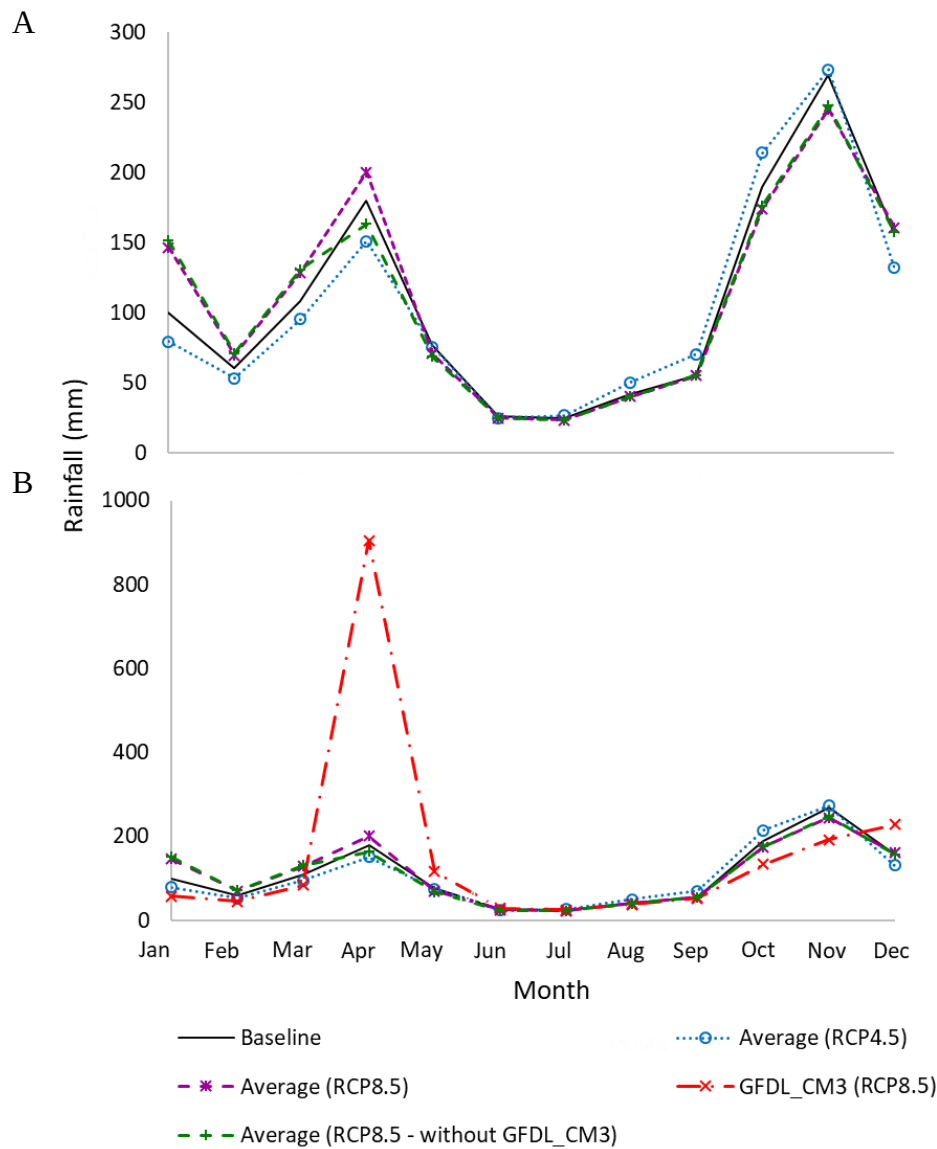


Figure 5.7. Distribution of future (2040–2069) and baseline (1980–2009) mean monthly rainfall without (A) and with (B) the GFDL_CM3.

Future mean annual rainfall of 30 years period generated by 4 GCMs (GFDL_CM3, MIROC5, IPSL_CM5A_MR and NorESM1_M) under RCP8.5 scenario showed that study area that belongs to Low Country Dry Zone received rainfall above the upper limit for the Dry Zone (1750 mm), suggesting the area will show characteristics of Intermediate Zone during the 2040–2069 period. Changes of annual and Proso millet growing seasonal rainfall and mean temperatures for 20 different GCMs (named A–T in Table 5.3) under both RCP4.5 and 8.5 are shown in Figure 5.8.

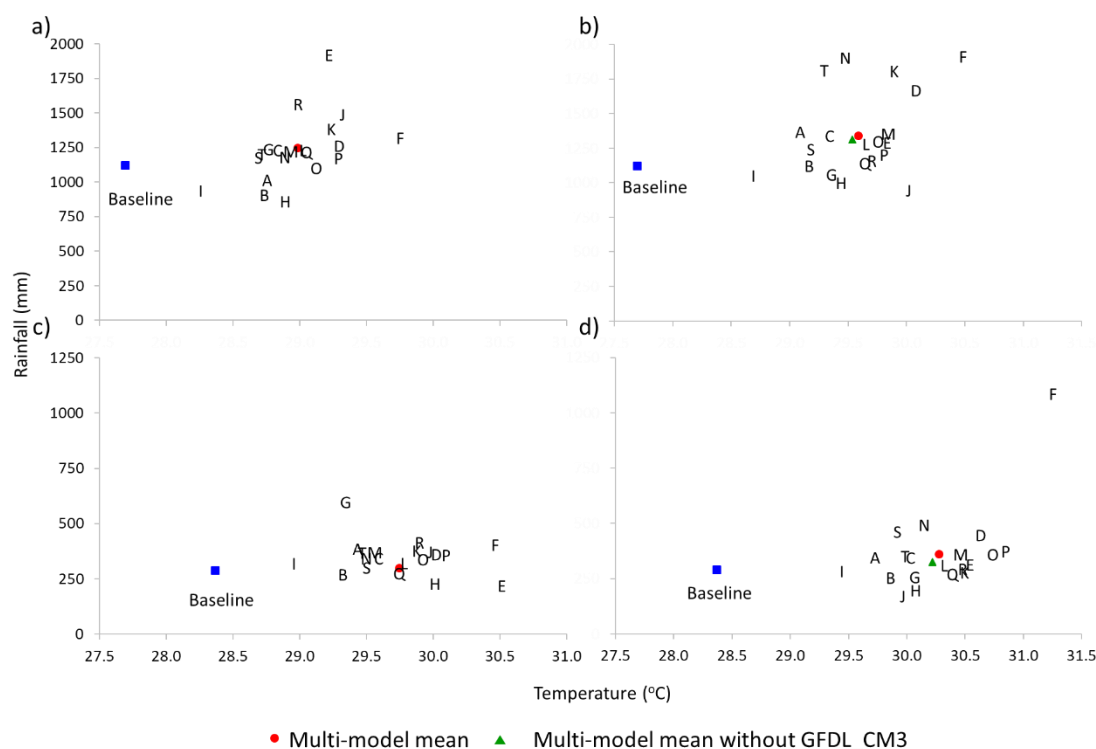


Figure 5.8. Annual (a and b) and Proso millet growing seasonal (c and d) rainfall and mean daily temperature in Bodagama, Sri Lanka during 2040–2069 period with compared to the baseline (1980–2009) period (blue square) in RCP4.5 (a and c) and RCP8.5 (b and d). Different letters (A – T) denote 20 different GCMs (Table 5.3) and the red dot is the mean value of 20 GCMs.

5.4.4. Proso millet production sensitivity to rainfall and temperature variation

The sensitivity of Proso millet production to changes in temperature and rainfall according to the C3MP 99 climate sensitivities are shown in Figure 5.9. Only the relationship between rainfall and temperature were studied because APSIM millet model was not parameterised to CO₂.

Simulated Proso millet yield increased by around 5% within a restricted climate change space of up to 2 °C of warming at increased rainfall (Figure 5.9). Accession L_12 showed the highest yield increment (10%) at 1 °C of warming under wetter conditions (50% increment of rainfall). The yield decreased with increasing temperature, regardless of whether rainfall increases or decreases, in all the tested accessions. Proso

millet yield reduction at 1 °C, 2 °C and 3 °C increment at zero rainfall change were 5–10%, 10–20%, and 20–30% and respectively. Temperature reduction to –1 °C without changing rainfall did not reduce Proso millet yield in all the accessions (L_1, L_11, L_12, L_14 and L_25) suggesting their ability to withstand slightly cooler environments.

Proso millet yield decreased with the reduction of rainfall in all the tested accessions. A 25% and 50% reduction of rainfall at zero temperature change reduced the yield by 25–30% and 60–65% respectively. Proso millet sensitivity to rainfall increment showed a similar pattern in all the accessions but in different magnitudes. The highest rainfall increment did not exhibit the highest yield increment in Proso millet. All the tested Proso millet accessions have a rainfall sensitive range on which they recorded the highest yield, but this range was different among accessions. The accession L_12 gave the highest yield in a wide range of rainfall increment (14–46%) suggesting its ability to withstand in higher rainy conditions. The increased yields in medium rainfall increment and decrease at a higher increment of rainfall (50%) at zero temperature change environments are consistent in all the accessions.

The mean change of rainfall and temperature of 20 GCMs (Table 5.3) for the 2040–2069 period under RCP4.5 and RCP8.5 scenarios were plotted with the C3MP results (Figure 5.9). It was found that Proso millet yield reduction was 0–5% for RCP4.5 (11% mean rainfall and 1.3 °C T_{mean} increment than baseline) and 0–10% for RCP8.5 (20% mean rainfall and 1.89 °C T_{mean} increment than baseline) when the sensitivity of Proso millet production to mean temperature and rainfall of 20 GCMs were concerned for the 2040–2069 period.

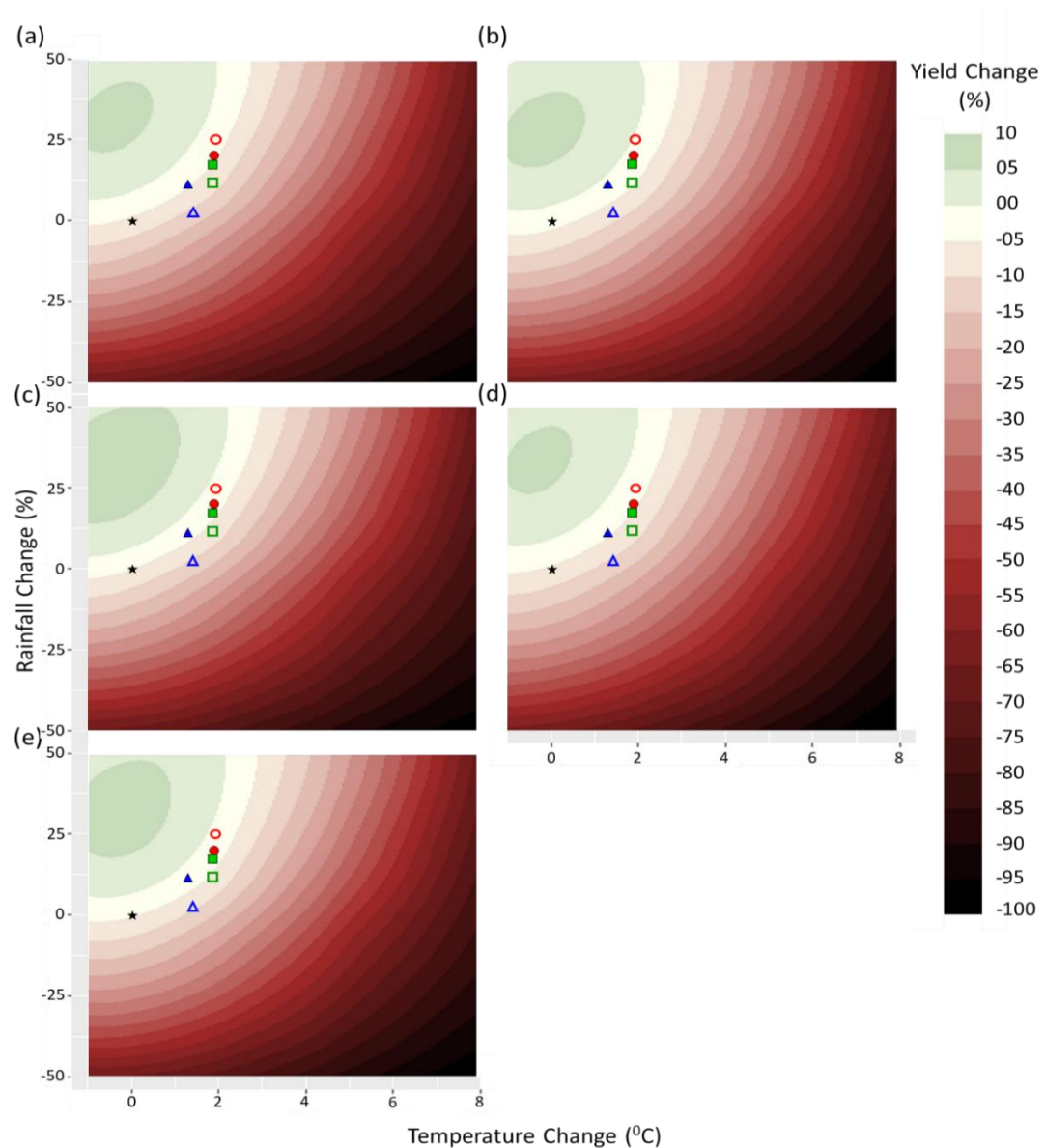


Figure 5.9. Yield sensitivity of five Proso millet accessions (a – L_1, b – L_11, c – L_12, d – L_14 and e – L_25) to rainfall and temperature change in Bodagama, Sri Lanka. The shaded blue triangle, red dot and green square represent the mean annual rainfall and temperature changes for RCP4.5, RCP8.5 and RCP8.5 without the GFDL_CM3 model (outlier) respectively. Not shaded triangle, dot and square represent the mean Proso millet growing seasonal rainfall and temperature changes as for the shaded shapes respectively.

The removal of GCM with extreme rainfall increment during Proso millet growing season (GFDL_CM3) did not change the percentage yield change category in 4 accessions except L_14 on which it was reduced by 5%. But the annual rainfall

increment of GFDL_CM3 was out of the C3MP rainfall sensitivity range. Mean rainfall and temperature change of Proso millet growing season was lower than the annual values in RCP4.5 while it was higher in the RCP8.5. Removal of the outlier GCM (GFDL_CM3) lowered the mean value than the RCP8.5 scenario.

5.4.5. APSIM millet yield prediction for the mid-21st century

The predicted Proso millet yields from APSIM millet model, using downscaled climate data for mid-century (2040–2069) under RCP4.5 and RCP8.5 scenarios were statistically analysed for the deviation from the baseline (1980–2009) yields. It was found that Proso millet yields of all the tested accessions (L_1, L_11, L_12, L_14 and L_25) were not significantly ($p > 0.05$) deviated from the baseline yields under both RCP4.5 and RCP8.5 scenarios. However, mean Proso millet yield for the 1980–2009 period (1707 kg ha^{-1}) was higher than the mean yield for the 2040–2069 period in all the tested accession for both RCPs. Percentage yield change of five Proso millet accessions for 20 GCMs (A–T in Table 5.3) are shown in Figure 5.10.

The accession L_25 recorded the highest mean yield for all the accessions under both RCP4.5 (1711 kg ha^{-1} , SD 227 kg ha^{-1}) and RCP8.5 (1535 kg ha^{-1} , SD 271 kg ha^{-1}). The L_14 showed the lowest yield in RCP4.5 (1479 kg ha^{-1} , SD 196 kg ha^{-1}) and RCP8.5 (1341 kg ha^{-1} , SD 235 kg ha^{-1}). The mean yield for all the accessions in all GCMs under RCP4.5 (1584 kg ha^{-1}) was higher than the RCP8.5 (1425 kg ha^{-1}). In RCP4.5, the lowest and the highest mean yields for all the accessions were 1108 kg ha^{-1} (GFDL_ESM2M) and 1988 kg ha^{-1} (GFDL_ESM2G) respectively. The IPSL_CM5A_LR recorded the lowest yield (567 kg ha^{-1}) and BCC_CSM1_1, the highest mean yield (1679 kg ha^{-1}) under RCP8.5.

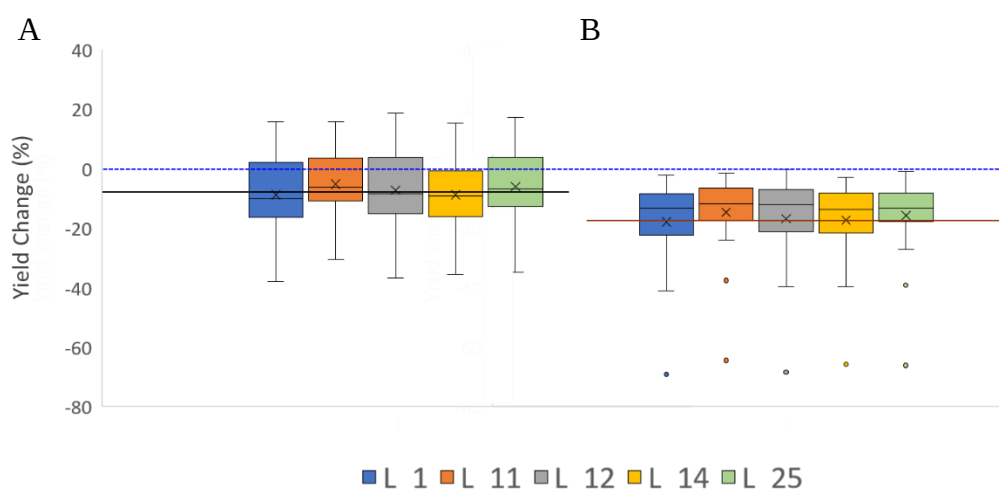


Figure 5.10. Box and whisker plots of mean yield changes (%) in 20 GCMs (A–T in Table 5.3) under RCP4.5 (A) and RCP8.5 (B) scenarios in the mid-21st century (2040–2069) in Bodagama Sri Lanka. Black and brown straight lines represent mean yield change of five accessions for 20 GCMs under RCP4.5 and RCP8.5 respectively while the blue line is for zero yield change.

Different GCMs exhibited different yield changes for five Proso millet accessions in the mid of 21st century. The variation of Proso millet yield in five different accessions for all the GCMs under RCP4.5 and RCP8.5 are shown in Figure 5.11.

The variation of future climate among different models has led to the variation of Proso millet yield in the mid-21st century. In RCP4.5, the average yield of 5 Proso millet accessions increased in 25% of GCMs (Figure 5.12). The highest percentage of climate models (40%) decreased Proso millet yield by 10% than the average for the baseline period. The climate change led to a Proso millet yield reduction greater than 20% in 10% of GCMs in RCP4.5. In RCP8.5, the yield decreased up to 10% in 40% of GCMs followed by up to 20% in 35% of GCMs. Only 5% of GCMs recorded a yield reduction greater than 60% from the baseline. None of the GCMs showed a yield increment under the RCP8.5 scenario.

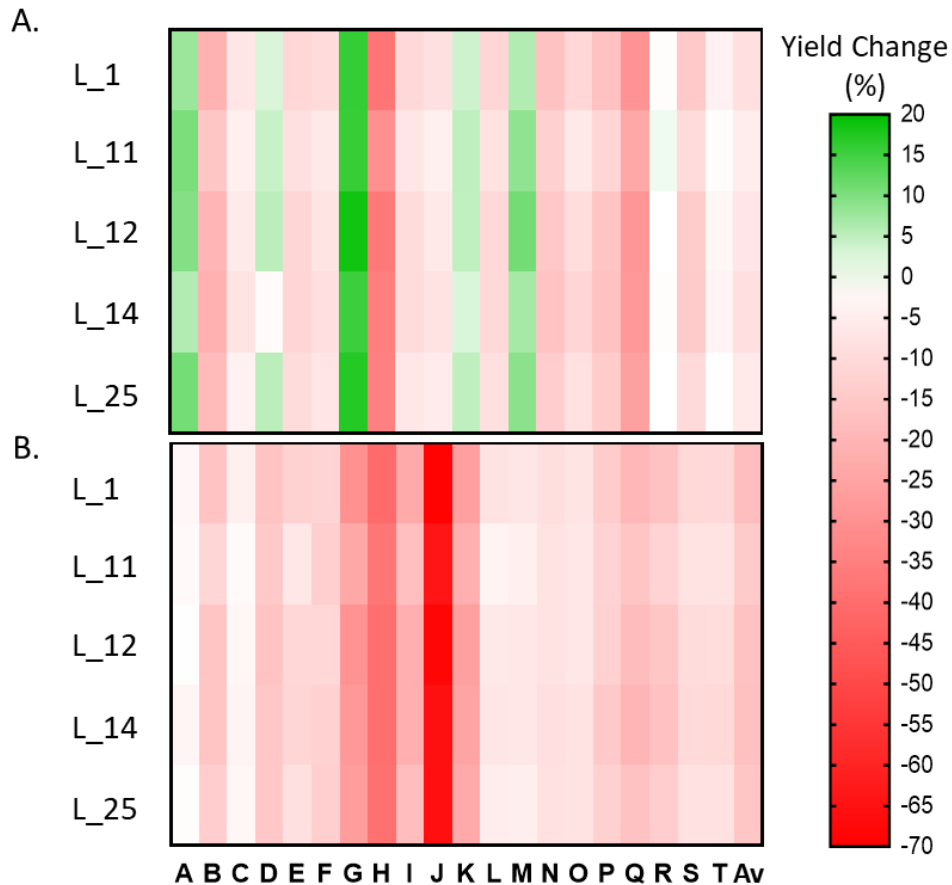


Figure 5.11. The heatmap for the variation of Proso millet yield change in five different accessions (L_1, L_11, L_12, L_14 and L_25) for all the GCMs (A–T in Table 5.3) and average (Av) for (A) RCP4.5 and (B) RCP8.5.

Out of 20 GCMs, only 4 GCMs (BCC-CSM1-1, GFDL-ESM2G, IPSL-CM5A-MR and MIROC_ESM_CHEM) showed yield increment for 2040–2069 period under RCP4.5 scenario in all the accessions. The MPI-ESM-MR showed yield increment in all four accessions except L_14. The yield predicted by all the models under RCP8.5 were lesser than the mean yield for the baseline period. However, mean Proso millet yield of all the accessions (L_1, L_11, L_12, L_14 and L_25) simulated by APSIM millet model were lower than the baseline (1980–2009) yield under both RCP4.5 (7.3%) and RCP8.5 (16.6%) scenarios for 2040–2069 period. The values were closer to yield change values in C3MP analysis (0–10% reduction) when only the rainfall and temperature sensitivity on Proso millet yield were analysed.

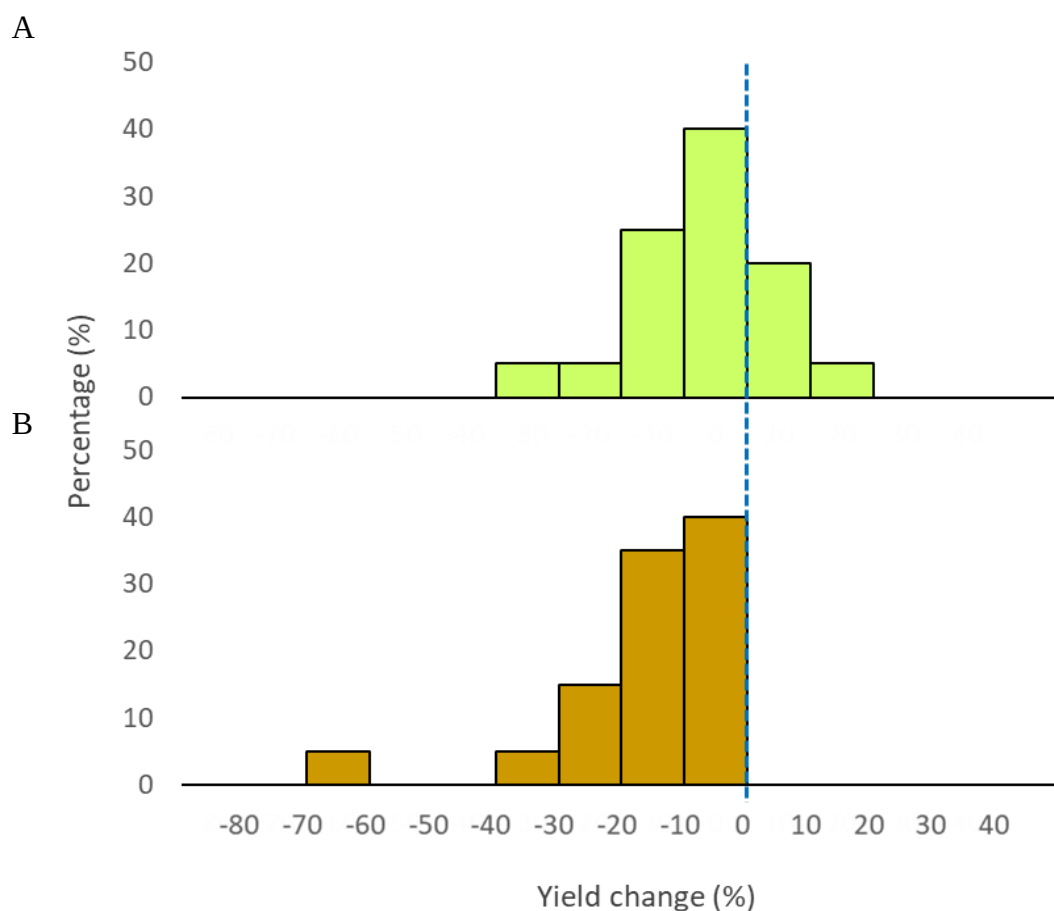


Figure 5.12. Relative Proso millet yield change for the 2040–2069 period with compared to baseline (1980–2009) period in all GCMs under RCP4.5 (A) and RCP8.5 (B). All yield change values of 5 Proso millet accessions were averaged.

5.5. Discussion

The future temperature projections recorded in this study are consistent with the IPCC global projections (IPCC 2013). The IPCC (2013) projected an increment of global temperature by 1.4 °C (ranged from 0.9 °C to 2 °C for RCP4.5 and 2.0 °C (ranged from 1.4 °C to 2.6 °C) for RCP8.5 during 2046–2065 period (IPCC 2013). The mean increment of temperature in Proso millet growing region in Sri Lanka for the 2040–2069 period (1.3 °C and 1.9 °C for RCP4.5 and RCP8.5 respectively) belongs to the IPCC (2013) projected range. Further, the projected temperature increment in Proso millet growing region agrees with the previous studies (1.5–2.8 °C for *Yala* and 1.1–2.4

°C for *Maha*) in North Western province of Intermediate Zone of Sri Lanka for 2040–2070 period (Zubair et al. 2015) and Walawe basin in the Southern part of the country (Jayatillake and Droogers 2004) described in section 5.2. However, rainfall projections showed both higher and lower values for mid-century than the baseline period and show the uncertainties among climate models. Higher model uncertainty was reported in the precipitation projections over Sri Lanka for 1901–2100 period when compared with India (Pattnayak et al. 2017) and the present study confirms these findings. The small spatial scale considered in the study (Hawkins and Sutton 2009; Zubair et al. 2015) hindered the accurate comparison and discussion on model uncertainty and variability. This should be better answered by analysing different geographic locations.

There has been a tendency towards a wetter future in the study area in recent decades (Chapter 3) that were also confirmed by others (Muthuwaththa and Liyanage 2013). However, both increasing and decreasing rainfall trends were observed in the country (Jayawardene et al. 2005). Future rainfall projections in this study agreed with the findings of Muthuwaththa and Liyanage (2013) that predict the lowering of the extent of Dry Zone due to increased annual rainfall, and Ampitiyawatta and Wijeratne (2015) who expect the expansion of Wet and Intermediate Zone boundaries towards the Dry Zone at the end of the century. However, the amount of rainfall increment projected in the present study was lower than the amount projected by Zubair et al. (2015).

The projected future climate of 20 GCMs showed differences among each other. Out of 20 GCMs used in this chapter, the GFDL_CM3 projected an extreme rainfall for April (RCP8.5) while it was not an outlier under RCP4.5 (Table 5.5 and Figure 5.8). The GFDL_CM3 is one of the best performing models to predict Indian Summer Monsoon (June–September) in different timescales (up to year 2099 – Menon et al. 2013; year 2051 to 2099 period – Sharmila et al. 2015) under the RCP8.5 scenario. The

predicted extreme rainfall belongs to First Inter Monsoon (Chapter 3) while the studies were done for the South West Monsoon period in Sri Lanka (Indian Summer Monsoon). However, the rainfall during June – September period was predicted well by the GFDL_CM3 (Table 5.5 and Figure 5.7). The implausible increment of April rainfall to 900 mm from this model (Figure 5.7) cannot be addressed by the available literature, therefore, further studies are needed on the behaviour and strength of GFDL_CM3 over Sri Lanka, specially under the First Inter Monsoon period. The multimodal mean with and without GFDL_CM3 was studied, therefore it will not affect the results of Chapter 5. Because the use of multi-model mean and several GCMs than one reduces the model uncertainties (Wallach and Thorburn 2017). Low confidence and higher uncertainty can be avoided by the use of a range of climate models (Sengupta and Rajeevan 2013).

Proso millet yields in all the tested accessions are likely to decrease with the expected warming, regardless of the variation of rainfall, however, low rainfall makes this case severe. The elevated temperature i) increases the potential evapotranspiration in water scarce soils that limit the water availability for roots to uptake, ii) increase the maintenance respiration per biomass unit that decreases the biomass production and iii) reduce the length of the crop cycle that also lower the biomass production, are identified as three key processes that cause yield reduction of millets and sorghum at warmer environments (Sultan et al. 2013).

The sensitivity of Proso millet to rainfall showed that Proso millet have their own rainfall increment rate on which they give the highest yields, and the highest yield was not from the highest rainfall increment. It was found that there are specific environmental parameters that have the most influence on Proso millet yield in Low Country Dry Zone Sri Lanka such as rainy days, amount of rainfall during different weeks of the lifespan of the crop and heat days, using APSIM simulated data (5.4.1). It

was reported that heavy rains after two weeks of planting Proso millet are destructive, causing poor plant stand by bury seeds too deep to emerge or create soil surface crust difficult for seedlings to penetrate (Lyon et al. 2008). Nielsen and Vigil (2017) studied the effect of environmental parameters influence on Proso millet yield and found that the rainfall during 12 – 18 August (59 – 65 DAS) has the highest impact on yield, on which the sowing was 14 June and harvesting was 15 September. Further studies are needed on the most effective and destructive rainfalls during Proso millet lifespan.

Different GCMs, time slices, crops, locations and methodologies hamper proper comparison of the yield projections of this study with other studies. However, based on the similar approach, but using APSIM and DSSAT models driven by future climate that has 4 GCMs (RCP8.5) similar to the present study (GFDL-ESM2M, MIROC5, HadGEM2-ES and MPI-ESM-MR), Zubair et al. (2015) projected a reduction of Paddy yield by 28%, 33%, 41% and 36% respectively in *Yala* season (DSSAT simulations) in the Intermediate Zone of Sri Lanka. But in contrast, APSIM simulations reported by Zubair et al. (2015) for the same season in the same location recorded yield increment in three GCMs (ranged from 3–9%) except HadGEM2-ES on which 2% reduction was observed. Proso millet yield reduction in this study is lower than DSSAT simulations (39%, 9%, 13% and 5% respectively), but higher than the APSIM simulations. It should be noted that paddy farming includes extensive use of irrigated water, fertiliser and crop husbandry practices that were not used in Proso millet cultivation. Further, the agroecological zone and soil characteristics of the study area are also different for the present study. However, this negative impact of Proso millet yield agreed with the previous findings of Sultan et al. (2013) who used SARRA-H model driven with climate projections from CMIP3 and CMIP5 models. It was found that the mean yield

of millet and sorghum decreased by 50% under medium term climate projections (2031–2050), averaged over 35 locations in West Africa (Sultan et al. 2013).

One of the limitations of the study was the APSIM millet model was not calibrated for CO₂, therefore the effect of CO₂ on Proso millet yield could not be studied. Being a C₄ plant, it is not expected that the higher yield reduction due to increased temperature is counteracted by the increased atmospheric CO₂, because the response of C₄ plants to increasing CO₂ is lesser than the C₃ plants (von Caemmerer and Furbank 2003). The carbon dioxide concentration is 3 to 6 times higher within C₄ plants than the atmospheric CO₂ concentration because RuBisCO (ribulose-1,5-biphosphate carboxylase-oxygenase), that reacts with CO₂ are localised to bundle sheath cells (von Caemmerer and Furbank 2003). Therefore, the cells saturate, and RuBisCO prevents the increasing CO₂ uptake with increasing CO₂ concentration (Long et al. 2006). However, the reduction of stomatal conductance that increases the WUE may increase the yield in C₄ plants (Long et al. 2004). It was found that doubling the carbon dioxide approximately increased yield by 30% in C₃ species and less than 10% in C₄ species (Lawlor and Mitchell 1991). However, previous studies showed that the increasing CO₂ caused yield increment in sorghum (Hatfield et al. 2011), a C₄ plant that also cultivated in Sri Lanka. Under drought conditions, a beneficial effect from enriched [CO₂] is prominent in C₄ crops like maize due to higher RUE and WUE (Manderscheid et al. 2014). Therefore, Proso millet that is cultivated under moisture stress conditions can take advantage of the increased [CO₂]. Further studies are needed on the [CO₂] sensitivity of Proso millet. However, it is necessary to use a different crop modelling tool to study the effect of changes in CO₂ on Proso millet yield since the current version of APSIM millet is not sensitive to CO₂ changes.

The severity of climate change impact on crop yield depends on the crop variety and the region of cultivation (Sultan et al. 2013). It was found that different crop models play in different ways in the same location (Zubair et al. 2015), therefore this should also be evaluated. None of the climate projections leads to predictions within APSIM of the maximum potential Proso millet yield (4 t ha^{-1}) in the mid-21st century in the growing region in the country. In Sri Lanka, Proso millet is found in subsistence farming systems with very low inputs such as no artificial irrigation and fertiliser application that was observed rarely (Chapter 2). Therefore, it is important to study the soil moisture conservation, water management, fertiliser application and advanced crop husbandry technologies and their impact on future yield and climate sensitivity of Proso millet in Low Country Dry Zone Sri Lanka.

5.6. Conclusions

This study evaluated the crop and climate modelling approaches to examine the sensitivity of Proso millet production to future climate using calibrated APSIM millet model. The projections for the future climate shows a clear increment of temperature in the mid-21st century under medium-lower (RCP4.5) and most extreme high greenhouse gas emission (RCP8.5) scenarios in all 20 CGMs studied. The studied models show a possibility of a wetter future in Thanamalwila for RCP4.5 (85% GCMs) and RCP8.5 (75% GCMs). Further, in RCP8.5, 20% of GCMs reported that the upper limit of Dry Zone (1750 mm) will be passed in the future (2040–2069). Proso millet yield projections for mid century showed a considerable diversity among GCMs. Yield increased in 4–5 GCMs (20–25%) under RCP4.5 while none of the GCMs reported yield increment under RCP8.5 scenario. The C3MP results revealed that the Proso millet yield increased with up to 2 °C of warming at wetter conditions and then decrease

with additional warming. A 1 °C increment of temperature decreased Proso millet yield by 5–10% at zero rainfall change. Proso millet has its own sensitivity range to rainfall on which the highest yield was recorded. Proso millet, that is cultivated in low input agricultural systems without irrigation and fertiliser (most fields), show increment and low reduction of yield in the mid-21st century compared to the baseline, suggesting the suitability of the crop in the climate changing world. The yields of key crops like paddy are predicted to have lower yields for similar changes in climate, therefore, Proso millet will be an ideal candidate for Low Country Dry Zone Sri Lanka to provide considerable yield under changing climate in mid-21st century.

5.7. Chapter Summary

- The future (mid-21st century) climate, Proso millet yield projections and the sensitivity of Proso millet to changes of temperature and rainfall were studied.
- Temperature increment in Proso millet growing area was projected by all 20 GCMs studied under both RCP4.5 and RCP8.5 scenarios while in rainfall, both increment and reduction were projected.
- The mean Proso millet yield simulated with APSIM for the 1980–2009 baseline climate (1707 kg ha⁻¹) was higher than the predicted yield for both RCP4.5 (1584 kg ha⁻¹) and RCP 8.5 (1425 kg ha⁻¹) future climate scenarios.

Chapter 6

General Discussion and Conclusions

With the recent evidence on climate change that is taking place in Sri Lanka and its impact to the agricultural sector (Esham and Garforth 2013; Zubair et al. 2015), the demand for studies on the impact of climate change on crop yield has increased. Research attention has mostly been received by major crops like paddy (De Silva et al. 2007; Dharmarathna et al. 2014; Zubair et al. 2015) and maize (Karunaratne and Wheeler 2016) while the climate resilience and yield of underutilised crops like Proso millet in the future climate has not been documented in Sri Lanka nor globally. Proso millet, a short duration and stress tolerant plant which has the ability to grow with a low amount of rainfall (Baltensperger 2002; Lyon et al. 2008; Swaminaidu et al. 2015) was used in this study. Because it is one of the key underutilised crops cultivated in LCDZ Sri Lanka (Malkanthi 2016) with a potential to be cultivated as a future crop under climate change (Habiyaemye et al. 2017) but has received lesser research attention.

A combination of field survey, field experiments and modelling approaches were used in this study to evaluate the climate sensitivity of Proso millet in the mid-21st century, Sri Lanka. The future yield was predicted (Chapter 5) using the calibrated and validated APSIM crop model (Chapter 4). The present situation of the cultivation (Chapter 2) and the climate characteristics in the growing area (Chapter 3) were evaluated initially. The originality contained in this study is that it combines the sensitivity analysis across the climate change concerning both temperature and rainfall, and the sensitivity of the yield to these climate changes was studied using a newly calibrated crop model (Chapter 4).

Past data on crop production were collected from the government agricultural data source (HARTI) to study the trends of the production. It was found that the reported Proso millet land extent has a downward trend with an extraordinary pattern that appears unreliable when compared with the data collected in this study for the 2015 growing season. The unreliable official data may be associated with the low attention and the negligence of the crop by the agricultural authorities. Therefore, further attention is needed for underutilised crops like Proso millet from the government authorities, especially from the Department of Agriculture. A priority should be given for minor crops like Proso millet since the government attention is always on commercial crops like paddy and maize. The Proso millet data can be missed because these cultivations sometimes found inside the forests. The capacity building is also important to collect accurate data on the cultivation. A limitation caused by the lack of past data set was the calibrated model could not be validated using yield data covering multiple years. The collection of reliable data on the production and the extent of cultivation will be helpful for future studies on yield trends and also for agricultural decision making in the growing region.

A farmer survey was done to study the present situation of cultivation in the growing region and harvest was collected from farmer fields that were covered by the survey. The reduction of observed Proso millet yield for 2015 growing season (31%) was higher than the average yield reduction for mid-century under RCP4.5 (7%) and RCP8.5 (17%) compared to the mean yield simulated by APSIM for the baseline period (1980–2009). The observed yield for 2015 *Yala* season was lower (1.180 t ha^{-1}) than the potential yield of 4 t ha^{-1} while none of the observed fields ($n = 41$) recorded the potential value. Proso millet is still cultivated in rainfed low input farming systems without using fertiliser, soil moisture conservation practices and under very low crop

management practices (land preparation, weeding, crop protection) even though the market price is nearly three times higher than the major crop rice. An improved application of existing knowledge and technology to cultivation is a big opportunity to improve the yield. Indeed, this is agreed by farmers as an important strength in favour of Proso millet cultivation (Chapter 2). Further studies are needed on the nutrient and soil moisture management in the Proso millet fields and their impact on the final yield. The calibrated and validated crop model can be used to study the effect of soil inputs such as organic and inorganic fertilisers and tillage practices for the yield as used for finger millet by Madegwa (2015).

Farmers use a high seed rate and a plant density, that is a few times higher than the recommended amount (DOASL). Because farmers believed that the yield losses from the damages associated with higher animal pests (elephants, wild boars) and the changes in climate can be compensated from the higher plant density. But the increment of the density decreased yield components of Proso millet (Chapter 2) that negatively affected the yields (Agdag et al. 2001). Farmers are not aware of the recommendations and the studies are scarce on the impact of plant density on Proso millet landraces. It is essential to focus research on the identification of proper plant densities that gives the maximum benefit to farmers under low input cultivation systems.

One of the key constraints identified by the farmers for the cultivation was lack of the quality seeds. A higher number of farmers (38%) used their own seeds for several generations. Proper varieties were also not found from the farmer fields. Therefore, the introduction of high yielding Proso millet varieties is important. Landraces/ farmer selected accessions can be used to improve the varieties as they have specific adaptive features (Karunaratne et al. 2011). Proso millet is still categorized as an underutilised crop that is grown in subsistence farming systems. But results indicated that it is a cash

crop to poor farmers in the study area because the main purpose of cultivation is for selling. Most of the farmers cultivated Proso millet due to the high income generated and easy cultivation practices. Identification of market facilities and gaps in the value chain is also important to popularise the crop.

Proso millet is cultivated in a specific period (*Yala* season) of the year because the rainfall during that part of the year is not sufficient for other crops (Chapter 2). With the newly developed definitions, it was found that the period that is favourable for crop cultivation in LCDZ is far shorter than the length reported in the literature (Zubair 2002; De Silva et al. 2007; Chithranayana and Punyawardena 2008; Wickramagamage 2015). Even though the average amount of seasonal rainfall is higher than the lower limit of rainfall (300 mm) for a successful Proso millet cultivation (Changmei and Dorothy 2014), the cultivation can be adversely affected by long-term dry spells and the distribution of rainfall within the season, as happened in the year 2015. Therefore, timely sowing is critical for a successful Proso millet cultivation. There is limited scope to plant earlier because that would affect the management of other crops from the previous season (Mall et al. 2006) and delayed planting of Proso millet makes the plants more susceptible for long-term dry spells from the vegetative growth stages. Being cultivated in one of the driest areas in the country without irrigation and moisture conservation practices, the crop can be damaged due to drought stress during any growth stages. Therefore, it is important to pay attention to soil moisture conservation and water management in the farm fields that also can be evaluated using the calibrated crop model.

The APSIM millet model was calibrated for genetically unknown 5 Proso millet accessions that were collected from farmer fields in the LCDZ. Crop phenology recorded a good agreement between observed and simulated values suggesting a good

calibration of genetic coefficients for the millet module of APSIM. The phenology, LAI, biomass and yield of 5 selected accessions were not significantly different among each other and genetic studies are being carried out to study the genetic variation among accessions (The University of Nottingham UK – not covered from this thesis).

The calibrated model was validated using farmers' yield data collected from LCDZ where variations in soil properties, plant densities and management practices were found. The simulated yields from the model were satisfactory when compared with the observed data but need improvement since they recorded both over and under-estimation in different fields. Site-specific adaptations of landraces (Karunaratne et al. 2011), highly variable plant density that cannot be captured by the model, different crop management practices (such as sowing depth) and different stresses (weeds, damages from higher pests) that were not simulated in the model can be suggested as the reasons for the observed variation when compared with the simulated yields. Only the yields were compared in the validation due to the lack of data on both growth and development. Therefore, it is important to have a validation experiment that creates opportunities to validate other growth and development parameters such as phenology, leaf area index and biomass partitioning at different stages. The data should be collected at different intervals through repeated visits to get more data from farmer fields. The different sowing dates, plant densities and crop management practise such as fertilising can be used in the validation experiment so that it can represent the variability in farmer fields. Further, the model can be validated from the data collected from the farmers' field for another growing season that also captures the actual growing conditions in the area. However, while a more thorough validation stage would be desirable, the newly calibrated crop model for Proso millet permitted opportunities to study the climate sensitivity and yield projections of the crop.

Plant available soil water content is one of the major limiting factors for Proso millet grain yield in farmers' fields (Figure 4.10). Being cultivated at one of the driest areas in the country, soil evaporation is higher while WUE is lower (Mapa et al. 2010). Therefore, maximum utilisation of rainfall and conservation of soil moisture is important to get a higher yield, but none of the farmers practised rain water harvesting or soil moisture conservation methods in Proso millet fields (Chapter 2). It was reported that plastic mulched ridge and furrow rainfall harvesting (PRFRH) system significantly increased biomass, leaf area and plant height of Proso millet in the semiarid region in China (Qu et al. 2012). Therefore, rainfall harvesting and evaporation reduction methods should be promoted among farmers to increase the yield. The calibrated crop model can also be used to study the soil water balance and WUE under different management practices.

The RUE values of Pearl millet were used in the model and caused an overestimation of the biomass. Therefore, accession specific data is needed for the accessions collected from DZ Sri Lanka before use in crop models. Other than the LAI and biomass, the base, optimum and maximum temperatures for Proso millet accessions may be different from the reported values of 10, 30 and 45 °C that were used in the calibrated model. Therefore, future studies are needed on the threshold temperatures of the selected accessions.

Existing crop models like APSIM has the ability to simulate a few types of crops (Keating et al. 2003). Different crop models predict growth and development and yield forecasting of the same crop in different ways (Zubair et al 2015; Salo et al. 2016). But, lack of genetic coefficients is a constraint to simulate different crop species and varieties (Jame and Cutforth 1996). Therefore, the same experimental data (Chapter 4) can be used to calibrate different crop models (like DSSAT and Aquacrop) and compare

future yields. According to C3MP analysis, Proso millet gives a higher yield at a broader temperature range (-1 to 2 °C) at increased rainfall when compared with the baseline climate. The results of C3MP analysis provides the guidance on the range of climates where reasonable Proso millet yields can be achieved, therefore, initiated opportunities to expand the cultivation in other regions of Sri Lanka. The calibrated model can be applied to other places in Sri Lanka or other countries where similar conditions and cropping practices exist. Further model testing should be done for different soils and climates before use in other locations.

Studies on site-specific climate change projections and the impact of climate change on agriculture are scarce in Sri Lanka, especially in the Dry Zone of the country. The mean seasonal rainfall increment (20 GCMs) of 3.0% (RCP4.5) and 11.8% (RCP8.5 – without GFDL_CM3) was projected for 2040-2069 period in the study area. The wetter future projected by GCMs for Proso millet growing season (65% of models for RCP4.5 and 60% of models for RCP8.5) with a proper distribution favours Proso millet cultivation while the increased rainfall will enable the possibility of cultivation of more water demanding crops in the drier area.

The accuracy of future yields is influenced by the quality of the climate data from GCMs (Cammarano et al. 2017) as well as the baseline climate. Due to the lack of consistent climate data in the study region, the Nasa MERRA data were used for fillings gaps, therefore the characteristics of baseline climate and the simulated yield can be changed. The use of different models and multi-model ensemble reduce the uncertainty in crop model predictions (Wallach and Thorburn 2017). The use of 20 GCMs (Table 5.3) in this study is a plus point, but it is also important to study the climate sensitivity and yield projections in other potential areas in Sri Lanka and in other countries. Because the sensitivity of a crop to temperature and rainfall variation and projected

yield is site-specific (Karunaratne et al. 2015) and will enable in decision making regards the expansion of the cultivation in the future.

Both yield increment and reduction in varying magnitudes were reported in different parts of the world under climate change (Zhao et al. 2017). With the increment of one degree Celsius, global mean yield of three major crops namely wheat, rice and maize is expected to decline by $6.0 \pm 2.9\%$, $3.2 \pm 3.7\%$ and $7.4 \pm 4.5\%$ respectively (Zhao et al. 2017). In Dry Zone Sri Lanka, maize yield predictions for mid-century (RCP8.5, 5 GCMs) reported 7–18% reduction in major season and it was severe in the minor season with 17–26% reduction (Karunaratne and Wheeler 2016). The average reduction of Proso millet yield by 7% (RCP4.5) and 17% (RCP8.5) in the future (2040–2069) is lower when compared with paddy (average reduction 33% for 5 GCMs in Intermediate Zone Sri Lanka for 2040–2070 period – Zubair et al. 2015), maize (Karunaratne and Wheeler 2016), millet and sorghum (50% reduction in West Africa for 2031–2050 period for 35 scenarios – Sultan et al. 2013). Proso millet also requires lesser inputs (irrigation and fertiliser) and crop management practices when compared with paddy and maize (DOASL). Since Proso millet gives a higher yield even with very low inputs, it can be suggested as a good candidate to feed people and as a source of income for poor subsistence farmers in the future under climate change. Therefore, Proso millet is a future crop which is important for food security and to generate income for subsistence farmers in Low Country Dry Zone Sri Lanka under changing climate in the mid-21st century. The effect of increasing [CO₂], which is expected under climate change could not be simulated as described earlier (section 5.5). However, being a C₄ crop, Proso millet can take advantage in the future due to the increment of WUE under increased [CO₂] (Long et al. 2004). Therefore, further yield increment of Proso millet is expected in the future.

Adaptation to climate change is one of the best options to reduce yield losses. Since irrigation is not practised in farmers' fields (Chapter 2) and soil water plays an important role in yield (Chapter 4), irrigation will be a potential adaptation method to increase the yield. This will also facilitate the higher WUE in Proso millet which is expected under future climate.

The climate beyond the mid-21st century (2040–2069) was not studied in this work. It is expected that global mean surface temperature will increase by 1.8 °C (ranged from 1.1 °C to 2.6 °C) under RCP4.5 and 3.7 °C (ranged from 2.6 °C to 4.8 °C) under RCP8.5 scenario in the end of the century (2081–2100) relative to the 1986–2005 period (IPCC 2013). Further, there are larger differences between the RCP4.5 and RCP8.5 scenarios at the end of the century than during mid-century (IPCC 2013; Knutti and Sedlacek 2013). Therefore, it is expected that yield losses in the end-21st century would be much larger under the RCP8.5 scenario.

In sum, this thesis describes the procedures and results of the first attempt to evaluate the climate sensitivity of Proso millet using crop-climate modelling approaches. This work can be used as a baseline study to evaluate the climate sensitivity of other underutilized crops. The growth and development, yields and climate sensitivity of Proso millet that can be simulated using the calibrated model can be used to develop ideotypes for future breeding of the crop under climate change.

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Appendix

Appendix 1

Soil analysis procedure

Moisture content

The undisturbed soil samples were collected using a steel core. The mass of the fresh weight with the core was measured and oven dried for 8 hours at 105 °C and then allowed to cool in a desiccator. The moisture content was calculated using the initial and dry weight.

Bulk density

Oven dried samples that were used for moisture determination were used to determine the bulk density. The diameter and the depth of the soil core were measured using a Vernier calliper and the volume of the core was calculated. The bulk density was calculated as

$$\text{Bulk density} = \frac{\text{Dry weight of sample}}{\text{Volume of sample}} \quad (\text{gcm}^{-3})$$

pH and Electrical Conductivity

Air dried 10.0 g of soil (<2 mm) was weighed into a beaker and 50 mL of deionised water was added. It was stirred with a glass rod for one minute and left for 30 minutes. The suspension was stirred once again for one minute and pH and electrical conductivity was measured immediately by a multi-parameter meter (Model HQ40d, Hach, US). The pH meter was calibrated for pH 7.0, 4.0 and 10.0 using the standard solutions before measuring soil samples.

Texture (Hydrometer method)

A 50 g of air dried soil was weighed and soaked overnight in 100 mL of 5% Calgon solution. The mixture was poured to a stirring pan and sufficient distilled water was added, then stirred for 2 minutes at 16000 rpm. It was then transferred to a hydrometer jar and top up to 1 litre mark with distilled water. The solution was mixed well by turning the cylinder completely upside down and back 20 times. Then 3 drops of amyl alcohol were added to the top of soil suspension to disperse the froth. Hydrometer was placed at 40 seconds and 2 hours. A blank reading (100 mL of 5% Calgon in 900 mL water) at the same temperature to correct the Calgon. To correct the hydrometer reading, 0.2 divisions were added for each 1°F above 68°F in the hydrometer reading. The corrected hydrometer reading at 40 seconds is H_1 , 2 hours is H_2 and the weight of soil is M_s , therefore, the soil texture was cellulated as followings,

$$\text{Sand \%} = 100 - (H_1/M_s) 100$$

$$\text{Clay \%} = (H_2/M_s) 100$$

$$\text{Silt \%} = 100 - (\text{Sand} + \text{Clay})$$

Colour

Air dried soil sample was spread in a petri dish and soil colour was determined according to the Munsell colour notation using Chroma meter (CR-400, Konica Minolta, Japan)

Total nitrogen

Digestion

One gram of finely powdered (0.5 mm sieve) soil was measured into a digestion tube (300 mL) and the sample was moistened with 2 drops of distilled water. One gram of catalyst mixture (kjeldahl tablet) and 8 mL of conc. H_2SO_4 was added and mixed by

swirling. The tubes were placed on the heater and digested (360 °C nearly 2 hours). After the digest has cleared, it was continued heating for another 30 minutes, allowed to cool and 30 mL of distilled water was added while swirling.

Distillation

A 25 mL boric acid (H_3BO_3) indicator solution was added to a 150 mL beaker and placed under the condenser of the distillation apparatus so that the end of the condenser is below the surface of the H_3BO_3 solution. Then, 50 mL of 25% NaOH was added and distilled for about 7 minutes until approximately 75 mL of distillate produced.

Titration

The distillate was titrated with 0.01M HCl until the colour change from green to pink.

Calculation

$$N\% = \frac{a-b}{s} (M * 1.4 * mcf)$$

Where,

a = mL of HCl required to titrate sample

b = mL of HCl required to titrate blank

s = weight of air dried soil sample in g

M = molarity of HCl

mcf = moisture correction factor (0.2)

1.4 = $14 * 10^{-3} * 100\%$ (14 = atomic weight of N)

Appendix 2

Household Survey for Proso millet (*Meneri*) Cultivation

Name of respondent: _____ Respondent no.: _____

Address of respondent: _____

Date of interview: _____ Village: _____

Telephone number: _____ *GPS coordinates:* _____

1. Personal information

Age

Below 35	
36-45	
46-55	
56-65	
Above 65	

Education Level

No formal education	
Up to grade 5	
Up to grade 8	
Up to grade 11	
Up to Advanced level	
Degree	

Occupation

Farming	
Teaching	
Government job	
Private sector	
Own business	
Other	

2. Household Information

Name	Relation with Respondent	Age (years)	Sex	Education Years of formal education/training	Occupation	
					Primary	Secondary
1	RESPONDENT					
2						
3						
4						
5						
6						

3. Landholdings

Land	Land type	Land extent (ha)	Soil type	Tenure	Source of supplemental	% Area irrigated	
						Wet season	Dry season

Which type of soil does Proso millet grow well?

Black soil	
Brown soil	
Red soil	

Yellow soil	
Grey soil	
Other	

4. Information on Cultivation of Proso millet

Land	Extent (ha)	Land type	Previous Crop	Next Crop	Season		Cost of production (Rs/ha)	Production Yield (Kg/ha)	Total Production (Kg)	Price (Rs/Kg)
					Planting	Harvesting				

5. Seed Source

Own saved	
Exchange with other farmers	
Donated	
Purchased	
Other	

If exchanged, donated or purchased, place, organization or person

6. Proso millet varieties grown

Do you know any varieties that existed in the past but have disappeared or replaced by other varieties?

If yes can you list them and specify the reason and time it was lost?

Available varieties

Traditional varieties	Improved varieties

7. What are the cultural practices done in Proso millet cultivation

Cultural practice	Time duration	No. of Employees
Land preparation		
Crop Establishment		
Agrochemical and fertiliser application		
Maintenance- weeding/thinning/irrigation		
Harvesting		
Post-harvest handling		

8. Reasons for cultivating Proso millet crop

Easy to cultivate	
Good taste	
High income	
Food source	
Soil improvement	
Medicinal purpose	
Other	

9. Usage of Proso millet (as a percentage)

Own consumption	
Seed purpose	
Sell	
Other	

How often do you consume Proso millet?

Contribution to income (percentage)

9. Strength and opportunities for cultivating Proso millet

Statement	Attitude				
	SA	A	N	DA	SDA
Knowledge on cultivation is available					
Skill on cultivation is available					
Land for cultivation is available					
Suitable soil is available					
Suitable Climatic condition is available					
Labour for cultivation is available					
Selling of excess production is available					
Drought tolerant					

10. Problems (Weaknesses and threats) for cultivating Proso millet

Statement	Attitude				
	SA	A	N	DA	SDA
Good quality seeds are not available					
Seeds are impure					
Knowledge on processing and value addition is not available					
Market facilities are not available					
There is a higher competition with modern commercial crops					
There is a negative attitude of consumers towards underutilised crops					
There are wildlife threats					

11. The attitude of farmers towards Proso millet cultivation

Statement	Farmer's Attitude				
	SA	A	N	DA	SDA
Proso millet cultivation is profitable					
Proso millet cultivation gives economic benefits for farmers					
Proso millet has nutritional value					
Proso millet has medicinal value					
Proso millet needs low cost for cultivation					
Proso millet needs low level of water					
Proso millet have less pests					
Proso millet has less diseases					
Proso millet contributes for the biodiversity					
Proso millet helps for environment protection					
Proso millet can tolerate climate changes					

12. Rainfall and crop cultivation pattern in the area

[illegible]

Appendix 3

The C3MP 99 climate sensitivity tests

Sensitivity Test #	Temperature Change (°C)	Precipitation Change (%)	CO ₂ Concentration (ppm)
1	0.7	-17	418
2	0.0	23	458
3	1.9	-22	524
4	7.5	10	766
5	3.6	24	673
6	1.0	34	403
7	2.8	38	551
8	4.8	8	576
9	3.9	-42	700
10	4.3	-33	333
11	6.9	35	704
12	2.5	-12	875
13	5.4	15	377
14	0.2	27	777
15	2.1	3	714
16	6.5	-32	768
17	2.4	-48	510
18	7.8	26	607
19	4.2	-46	346
20	7.3	-28	544
21	7.1	-35	500
22	6.8	15	825
23	1.1	41	604
24	5.8	21	807
25	5.1	32	494
26	3.2	39	366
27	3.1	-40	732
28	7.9	-3	591

29	3.1	34	866
30	3.4	13	585
31	5.6	45	412
32	2.5	44	660
33	-0.1	-43	744
34	5.5	-9	572
35	4.0	-20	490
36	4.6	-38	839
37	6.3	-37	883
38	0.9	32	545
39	7.2	44	453
40	1.6	49	691
41	5.2	-13	454
42	2.0	-16	504
43	0.5	-7	537
44	4.7	-25	518
45	6.7	-11	486
46	1.3	-26	340
47	2.7	-11	424
48	5.9	-19	580
49	4.3	-9	793
50	-0.9	31	435
51	0.1	33	384
52	4.9	22	440
53	3.6	30	724
54	3.8	-5	836
55	6.4	4	642
56	6.3	11	433
57	1.4	-29	871
58	-0.2	11	475
59	7	-21	856
60	7.3	-24	829
61	4.5	-45	847

62	-0.3	-21	648
63	-0.5	5	629
64	0.6	47	861
65	-0.8	18	355
66	5.1	20	638
67	0.2	6	719
68	4.4	0	783
69	6.1	37	482
70	2.4	-6	399
71	6.6	-34	798
72	1.7	24	887
73	1.8	1	563
74	5.9	-16	898
75	3.5	19	526
76	1.2	-40	394
77	5.2	-50	554
78	0.4	9	679
79	7.2	14	727
80	0.9	7	663
81	-0.4	40	514
82	-0.6	12	426
83	5.7	-1	406
84	5.4	-44	754
85	5.5	21	621
86	7.6	-36	380
87	6.0	-27	444
88	2.7	2	815
89	7.5	0	645
90	-1.0	29	670
91	4.1	28	802
92	2.2	48	655
93	3.9	-35	689
94	1.7	43	587

95	0.3	-44	774
96	4.9	-47	709
97	6.2	17	852
98	2.2	39	599
99	1.1	6	737

Appendix 4

Environmental parameters that may have the most influence on Proso millet yield which were analysed by stepwise linear regression

Abbreviation	Description
O _R	Onset of growing season (defined in Chapter 3)
RF _{tot}	Total rainfall (mm) from 26 March to 02 June (Average Proso millet growing period)
D _{RF}	Total rainy days from 26 March to 02 June
D _D	Total dry days from 26 March to 02 June
RF ₁	Rainfall from 26 March to 01 April (date of sowing to 6 DAS)
RF ₂	Rainfall (mm) from 02 April to 08 April (7 to 13 DAS)
RF ₃	Rainfall (mm) from 09 April to 15 April (14 to 20 DAS)
RF ₄	Rainfall (mm) from 16 April to 22 April (21 to 27 DAS)
RF ₅	Rainfall (mm) from 23 April to 29 April (28 to 34 DAS)
RF ₆	Rainfall (mm) from 30 April to 06 May (35 to 41 DAS)
RF ₇	Rainfall (mm) from 07 May to 13 May (42 to 48 DAS)
RF ₈	Rainfall (mm) from 14 May to 20 May (49 to 55 DAS)
RF ₉	Rainfall (mm) from 21 May to 27 May (56 to 62 DAS)
RF ₁₀	Rainfall (mm) from 28 May to 02 June (63 to 68 DAS)
Tmax30	Number of days from 01 May to 02 June (flag leaf initiation to end of the crop) with maximum temperature greater than 30 °C
Tmax32	Number of days from 01 May to 02 June (flag leaf initiation to end of the crop) with maximum temperature greater than 32 °C
Tmax34	Number of days from 01 May to 02 June (flag leaf initiation to end of the crop) with maximum temperature greater than 34 °C