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Calibration and Validation of APSIM Millet Model for Proso millet (*Panicum miliaceum* L.) Accessions as a Basis for Crop Diversification

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ABSTRACT

Purpose: *Proso millet (Panicum miliaceum L.) is an underutilised minor millet grown as a rain-fed crop in subsistence farming systems in tropical African and Asian countries including Sri Lanka. It is identified as a climate-resilient crop that exhibits a huge potential to diversify conventional farming systems, however few modelling studies have assessed this crop, especially in the tropics. The objective of this study is to calibrate and validate Agricultural Production Systems Simulator (APSIM) model for Proso millet.*

Research Method: *The millet model of APSIM that was developed based on Pearl millet was calibrated for five farmer-selected Proso millet accessions using the data gathered from two field experiments. Yield data collected from 35 farmers' fields under different crop management practices were used to validate the model.*

Findings: *The observed phenology, leaf area index, above ground biomass and grain yield were not significantly different ($p > 0.05$) from the simulated values of the calibrated model. The observed yields (1187±336 kg ha^{-1}) in the farmers' fields were not significantly ($p > 0.05$) different from the simulated yields (1208±255 kg ha^{-1}), suggesting a good calibration of the model.*

Research Limitations: *Lack of field data under different abiotic stress conditions is a limitation for further validation of the model.*

Originality/ Value: *APSIM millet model has not been tested for Proso millet previously. Derived genetic coefficients were successfully used to simulate Proso millet production.*

Keywords: *crop modelling, minor millets, model calibration, underutilised crops*

INTRODUCTION

Proso millet (*Panicum miliaceum* L.) is an underutilised minor millet, but staple food in parts of tropical Asian and African countries (Habiyaremye *et al.*, 2017). It is also found in subsistence rain-fed farming systems of Low Country Dry Zone Sri Lanka. The primary sources of demand are the rural farming population, where it is consumed as a substitute for rice. It is the staple food in parts of Africa and Asia (Habiyaremye *et al.*, 2017) and the farmers in the developing parts of the world grow Proso millet as a subsistence crop with local landraces for dietary requirements as well as for income generation (as a cash crop) (Ghimire *et al.*, 2018).

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Even though Proso millet is categorised as an underutilised crop, a substantial potential exists as a crop that can diversify conventional subsistence farming systems. Its nutritional composition is superior (protein content >10%) to other cereals (Amadou *et al.,* 2013) and used in Sri Lankan folkloric medicine. In Sri Lanka, Proso millet is mainly cultivated in *Chena* farming systems, as a rain-fed crop, where minimum tillage conditions are used with low inputs. Production systems of Proso millet in the country are dominated by accessions selected by farmers that were saved from the previous harvest, sown in late March of *Yala* season and harvest in late May–early June (Wimalasiri *et al.,* 2017). Seeds are purchased rarely, and they are passed from one growing season to another.

Proso millet is identified as a drought tolerant crop that produces sufficient yield in environments unfavourable to other crops (Habiyaremye *et al.,* 2017). It survives and gives yield under conditions with annual rainfall as little as 200–450 mm (Krishna, 2013). No systematic studies on climate sensitivity, adaptation and yield potential have been carried out on Proso millet in Sri Lanka nor globally. Therefore, the information on yield response to climate variables and crop management practices could be helpful to farmers on decision making and to enhance the yield of Proso millet.

The productivity of crops under changing climate can be studied using crop models to evaluate agricultural adaptation options which could help policymakers and local stakeholders in decision making (Oteng-Darko *et al.,* 2013; Rauff and Bello, 2015). Crop models simulate plant growth, development and yield as functions of environment, management and defined genetic characteristics (Karunaratne *et al.,* 2010; Rauff and Bello, 2015). Very few attempts were made on the modelling of Proso millet crop. Soil nitrogen, Proso millet seed yield and crop residue were simulated to study the performance of crop rotation in the United States using 'Great Plains Framework for Agricultural Resource Management' (GPFARM) Decision Support System (Andales *et al.,* 2003). Andales *et al.,* (2003) calibrated the model using the potential harvest index and leaf area index (LAI). The CSM–CERES–Sorghum module in DSSAT v4.0 (Hoogenboom *et al.,* 2004) 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). The soil moisture content, LAI, biomass and seed yield were used to parameterise the model and the data from the same experimental field were used to validate the model (Saseendran *et al.,* 2009). A software Phenology MMS (McMaster *et al.,* 2011) simulates the phenological responses of Proso millet to water stress in the Great Plains, USA. The same data set of Saseendran *et al.,* (2009) was used to simulate yield and economic net returns at different plant available water levels in dryland winter fallow system in the Great Plains (Saseendran *et al.,* 2013) using The Root Zone Water Quality (RZWQM2) model (Ahuja *et al.,* 2000). However, Proso millet that is cultivated as subsistence crop in Sri Lanka or other growing regions was not studied previously using modelling approaches. Also, Agricultural Production Systems Simulator (APSIM) crop model (Holzworth *et al.,* 2014) was not tested for Proso millet crop.

Among crop models, APSIM is one of the leading simulation tools for modelling agricultural systems (Keating *et al.,* 2003). It was developed to simulate different biophysical process in farming systems, concerning both ecological and economic outcomes with climatic risk and has been applied over a range of crops and environments across the world (Holzworth *et al.,* 2014). The model has been used worldwide for different applications that includes designing farming systems, supply chain analysis in agri-business, supporting on-farm decision making, to simulate the performance of different crops under diverse management decisions, to analyse risks and to assess seasonal climate forecasting, waste management guideline development and as a research guide (Keating *et al.,* 2003). APSIM applications in Sri Lanka were mainly reported on field crops (Nissanka *et al.,* 2015; Wallach *et al.,* 2017) and identified as a promising tool to model the Proso millet production in Sri Lanka.

This is the first study where APSIM millet model has been tested for Proso millet. The objectives of this study are (1) to study the phenology, LAI, above ground biomass and grain yield of five Proso millet accessions originating from farmer fields in the Dry of Zone of Sri Lanka; (2) to assess parameters for the calibration of APSIM millet model for selected Proso millet accessions and (3) to validate the calibrated model for farmer fields in Sri Lanka. The calibrated and validated model will be used to predict the Proso millet yield under future climate and climate sensitivity that will be described in a separate article.

MATERIALS AND METHODS

APSIM Millet Model Description

As APSIM is not parameterised for Proso millet, the millet model 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 millet model in APSIM. Similar ecological, functional and agronomic characteristics of both millet types (Krishna, 2013) make pearl millet a suitable substitute for Proso millet for APSIM simulations.

The APSIM millet model simulates daily growth and development of Pearl millet crop (van Oosterom *et al.,* 2001a). Field experimental data from ICRISAT–Patencheru were used to parameterise the millet model. The model is specially designed to capture the tillering habit of the crop. The ability of the millet model to simulate the growth and development of individual tillers is a distinct feature. The model is capable of adequately predicting LAI, biomass and seed yield over a wide range of genotypes and photoperiods (van Oosterom *et al.,* 2001a,b, 2002; Holzworth *et al.,* 2014).

As climate parameters, the model requires daily temperature (minimum and maximum), rainfall and solar radiation. Millet growth responds to soil nitrogen (SoilN model) (Probert *et al.,* 1998) and soil water supply (SoilWat model). In phenology of millet module, there are 11 crop growth stages and thus, ten 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. Sowing to germination stages are controlled by soil moisture while all other stages are determined by the thermal time accumulation. 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. Rate of tiller appearance is controlled by the accumulation of thermal time or biomass that depends on the space between plants. Residues pass to Residue (Probert *et al.,* 1998) and SoilN once the crop is harvested (Keating *et al.,* 2003). The model details on phenology, leaf area index and biomass accumulation will be further described under Results section.

Selection of Proso Millet Accessions

Distinct Proso millet seed samples (hereafter mentioned as accessions) used in each experiment were selected to represent different seed sources and locations in Proso millet growing regions of Moneragala and Hambanthota districts in Sri Lanka (6.41–6.44°N, 81.08–81.12°E). They were grown in different soils under diverse management practices. All farm fields belong to DL1b agro-ecological zone (a region in the southern Sri Lanka characterised with an average of 1100–1750 mm of annual rainfall) of the country (Punyawardena, 2008). 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 (Wimalasiri, 2019) (Table 01).

Table 01: Geographical distribution and an average yield of selected Proso millet accessions used 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 1 were calculated from the harvest of the previous growing season (Yala 2015).*

Experimental Details

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

Calibration experiments: Data to calibrate the millet model were obtained from two field experiments conducted at the Faculty of Agricultural Sciences, 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).

Experiment 1 was carried out during a drier period of August–October 2016 (mean temperature of 27.1 °C, total rainfall of 4.5 mm). The land was ploughed by mouldboard plough to loosen the compacted soil. Approximately 1000 kg ha^{-1} cow dung and 750 kg ha^{-1} goat dung were evenly distributed throughout the experimental field ten days before planting. Parallel to the organic fertiliser, approximately 500 kg ha^{-1} biochar prepared from paddy husks were also evenly distributed in the field. The field was ploughed again by rotary plough to mix the soil and organic matter and experimental unit (plots) of 1m x 3m were prepared. As the treatment, five Proso millet accessions were allocated into different plots with three replicates in a Randomised Complete Block Design (RCBD).

A germination method used by paddy farmers in Sri Lanka was used to germinate the seeds due to a low number of seeds from plants collected by farmer fields and low germination percentage. 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; Urea 125 kg ha^{-1}, Muriate of Potash 50 kg ha^{-1} and Concentrated Super Phosphate 50 kg ha^{-1} (Department of Agriculture Sri Lanka – DOASL). Proso millet seedlings were transplanted 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 and 75 kg ha^{-1} of urea was applied 14 days after transplanting. Plants were protected against pests by both chemical and physical methods. Fipronil 16ml/16L and Abamectin 18 g/l EC were sprayed to control red spider mites (*Tetranychus spp*) and thrips (*Cirtothrips dorsalis*) respectively. Panicles were covered by tissue papers to avoid cross pollination. The field was irrigated daily and the amount of water applied in each day was recorded.

Experiment 2 was carried out during a rainy season (February–April, mean temperature 26.3 °C, total rainfall 492.5 mm) in year 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. Urea (75 kg ha^{-1}) was applied 14 days after planting. Due to a drier period at the beginning of the crop, the field was irrigated from sowing to 10 DAS. Otherwise, the crop was grown as rainfed.

Experimental measurements: Soil samples from the experimental field were collected from four depths at 0–15, 15–30, 30–60 and 60–100 cm with three replicates before planting to measure the initial soil fertility status (Table 02). Daily minimum and maximum temperatures and rainfall data were recorded at the experimental site. NASA Prediction of Worldwide Energy Resource (POWER) dataset (Zhang *et al.,* 2009) and available on a 1–degree grid were used to obtain solar radiation data during two experimental periods since the measurement of solar radiation is not available at the experimental site.

In both experiments, well-bordered five representative plants were selected randomly from each plot and tagged. From each tagged plant, fully expanded leaves and the number of tillers 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. For growth and dry-matter distribution analysis, randomly selected 3 plants from each plot (9 plants per accession) were uprooted weekly and separated into different plant parts. They were oven-dried for 48 hours at 80 °C temperature and dry weight was measured. Leaf area was measured in weekly intervals. 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 were measured using leaf area meter (LI–3100C, LI–COR Inc. USA). Proso millet plants were harvested at full maturity stage. Grain yield and grain weight were used to calculate grain number (van Oosterom *et al.,* 2002).

Table 02: Soil data used to calibrate the APSIM millet model

Depth (cm)	BD (g/cm^3)	LL 15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	pH	EC (dS/m)	OC (%)
0-15	1.12	0.29	0.54	0.59	6.79	0.17	1.04
15-30	1.22	0.29	0.53	0.58	6.75	0.17	0.89
30-60	1.35	0.29	0.54	0.59	6.74	0.17	0.58
60-100	1.35	0.29	0.54	0.59	6.74	0.17	0.58

BD= Bulk density, LL= Lower limit (permanent wilting point), DUL=Drainage upper limit (Field capacity), SAT=Saturation, EC= Electrical conductivity and OC=Organic carbon

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 period. Most farmers cultivate Proso millet during March–June period in this region (*Yala* season). These fields are varying in seed sources, sowing and harvesting dates, plant densities, crop management practices and soil properties. Climate characteristics of the area, the details of the experiment, sample collection and measurements were previously described (Wimalasiri *et al.,* 2017), therefore, only a summary is presented here.

Three randomly selected locations in farmers' fields were marked using one square meter quadrat in 41 farm fields. The harvest was collected from each field and yield analysis was performed as described earlier. Farmer survey was conducted using researcher administered pretested questionnaires to collect information on sowing and harvesting dates, and crop management practices. Soil samples were collected from each field with three replicates and analysed.

Model Calibration

To ensure the suitability of millet module for modelling Proso millet, simulations were conducted using various crops that include sorghum, maize and barley 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.

Calibration of APSIM – millet, Version 7.8 (Keating *et al.,* 2003) was undertaken for the five Proso millet accessions collected from farmers' fields in Sri Lanka. Soil modules in APSIM model were calibrated using the data summarised in Table 02. The crop phenology was simulated using thermal time (growing degree days – GDD). In the APSIM millet model, thermal time was calculated using the base, optimum and maximum temperatures of 10 °C, 33 °C and 47 °C respectively (van Oosterom *et al*., 2001b). The cardinal temperature values were adjusted for Proso millet crop in the XML file as; 10 °C, 30 °C and 45 °C for base, optimum and maximum temperatures respectively (Anderson, 1994; Lyon *et al*., 2008). 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). All the simulations in calibration were performed with the assumption that the crop is not water stressed. Trial and error method was used to derive the best fit curve to match the simulated dates of emergence of seedlings and flag leaf, flowering, start of grain filling, maturity and harvest ripe to the observed dates. Then, the calibrations were done based on the comparison between simulated and observed LAI, above ground biomass and grain yield. The best fit with minimum differences between observed and simulated yield was determined by adjusting the potential grains per head. Genetic parameters of five Proso millet accessions that were adjusted to match the crop phenology are summarised in Table 03.

Model Validation

Proso millet yield data gathered from farmers' fields at Bodagama Sri Lanka were used to validate the model. Out of the 41 farmers' fields, 35 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 biomass and grain yield (van Oosterom *et al.,* 2002). The highest tested plant density (20 plants m^{-2}) by van Oosterom *et al.,* (2002) was used in model validation.

Table 03: 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	Accession				
		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

TT = Thermal time

A number of methods were used to compare the goodness-of-fit between simulated and observed values and to evaluate the model performance. The systematic behaviours of graphs were visually evaluated. The Nash and Sutcliffe model efficiency criteria (Nash and Sutcliffe, 1970) (Equation 1), hereafter mentioned as N–S, was used to measure the efficiency of the model.

$$N - S = 1 - \frac{\sum_{i=1}^{n} (M_i - S_i)^2}{\sum_{i=1}^{n} (M_i - \mu)^2} \quad (1)$$

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 a very poor fitting model.

Wilmott index (d), known as index of agreement, measures the model prediction error between observed and simulated values (Equation 2) (Willmott *et al*. 2012). The value 1 indicates the perfect match between two datasets while it can be varied within 1 and 0. Zero indicates no agreement.

$$d = 1 - \frac{\sum_{i=1}^{n} (M_i - S_1)^2}{\sum_{i=1}^{n} (|S_i - \mu| + |M_i - \mu|)^2} \quad , \quad 0 \leq d \leq 1 \quad (2)$$

The differences between observed and simulated values were measured using Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (M_i - S_i)^2}{n}} \quad (3)$$

where, M is measured/ observed values, S is simulated values, n is the number of observations and μ is the mean of measured/ observed values. The coefficient of determination (R^2) determines the strength of the linear relationship between the observed and simulated values.

RESULTS

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 using equation 4.

$$GDD = \sum_{t=3}^{N} DD_t, \quad DD = \begin{cases} 0 & if\ T_t < T_b \\ T - T_b & if\ T_b \leq T_t \leq T_o \\ T_o - T_b & if\ T_t > T_o \end{cases} \tag{4}$$

Where, t represents three hourly time steps, N means the total hours in the season, DD is degree days and T_b and T_o are base and optimum temperatures respectively. A base temperature (T_b) of 10 °C and optimum temperature (T_o) of 30 °C were used.

Experimental results: Simulation of the phenology was the first aspect evaluated for five Proso millet accessions 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) in two experiments respectively.

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 01).

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 (Equation 5):

$$Y = Y_0 \exp\left(a (X - X_0)^2 + b (X - X_0)^3\right) \tag{5}$$

Where, Y and Y_0 are 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 respectively. The coefficients are functions of total leaf number (TLN). The 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 (van Oosterom *et al.,* 2001a).

Following equations (6 – 9) were used in the APSIM model to calculate the variables in equation 5 using TLN (van Oosterom *et al.,* 2001a) as,

$$X_0 = 3.58 + 0.60\ TLN \tag{6}$$

$$Y_0 = 34.8 + 7.4\ TLN \tag{7}$$

$$a = 0.00955 + (0.0608/ (1 - 0.1293\ TLN)) \tag{8}$$

$$b = 0.00144 + (0.0025/ (1 - 0.11\ TLN)) \tag{9}$$

Experimental results: The observed maximum leaf area index (mLAI) was the 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 02), i.e., the highest mLAI was from experiment 2 and it ranged from 3.58 (L_14) to 3.65 (L_25).

The observed and simulated LAIs were not significantly different ($p > 0.05$) in all five accessions in both experiments according to the student's t-test. On average, a higher agreement between observed and simulated LAI was recorded from the experiment 1 (dry period) (N–S 0.92±0.04, RMSE 0.28) than the experiment 2 (rainfed) (N–S 0.77±0.03, RMSE 0.56). The LAI of accession L_12 was simulated with higher accuracy (N–S 0.81, RMSE 0.52) than for other accessions by the fine-tuned model.

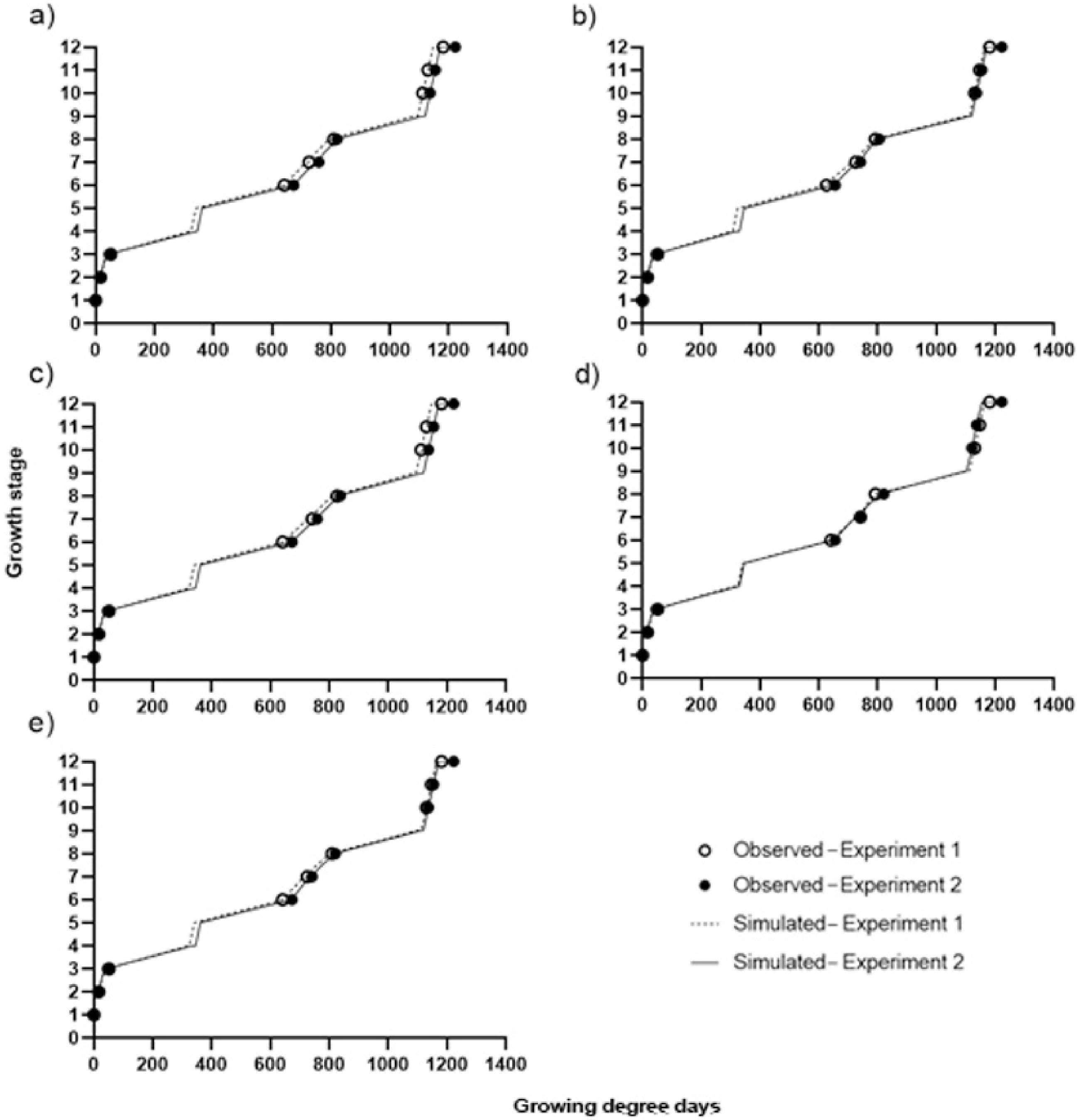

Figure 01: **APSM simulated vs observed phonological development stages of five Proso millet accessions (a. L_1, b. L_11, c. L_12, d. L_14, e. L_25) express based on the cumulative thermal time (growing degree days; GDD). Developmental stages were defined based on APSIM millet module, where 1=sowing, 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.**

Biomass - model description: In the APSIM model, daily biomass accumulation is a function of water availability for transpiration (Equation 10) and radiant energy (Equation 11).

DM_transp = sw_supply_sum * TE (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, which is based on daily temperature values.

DM_potential = RUE *Radiation_Interception (11)

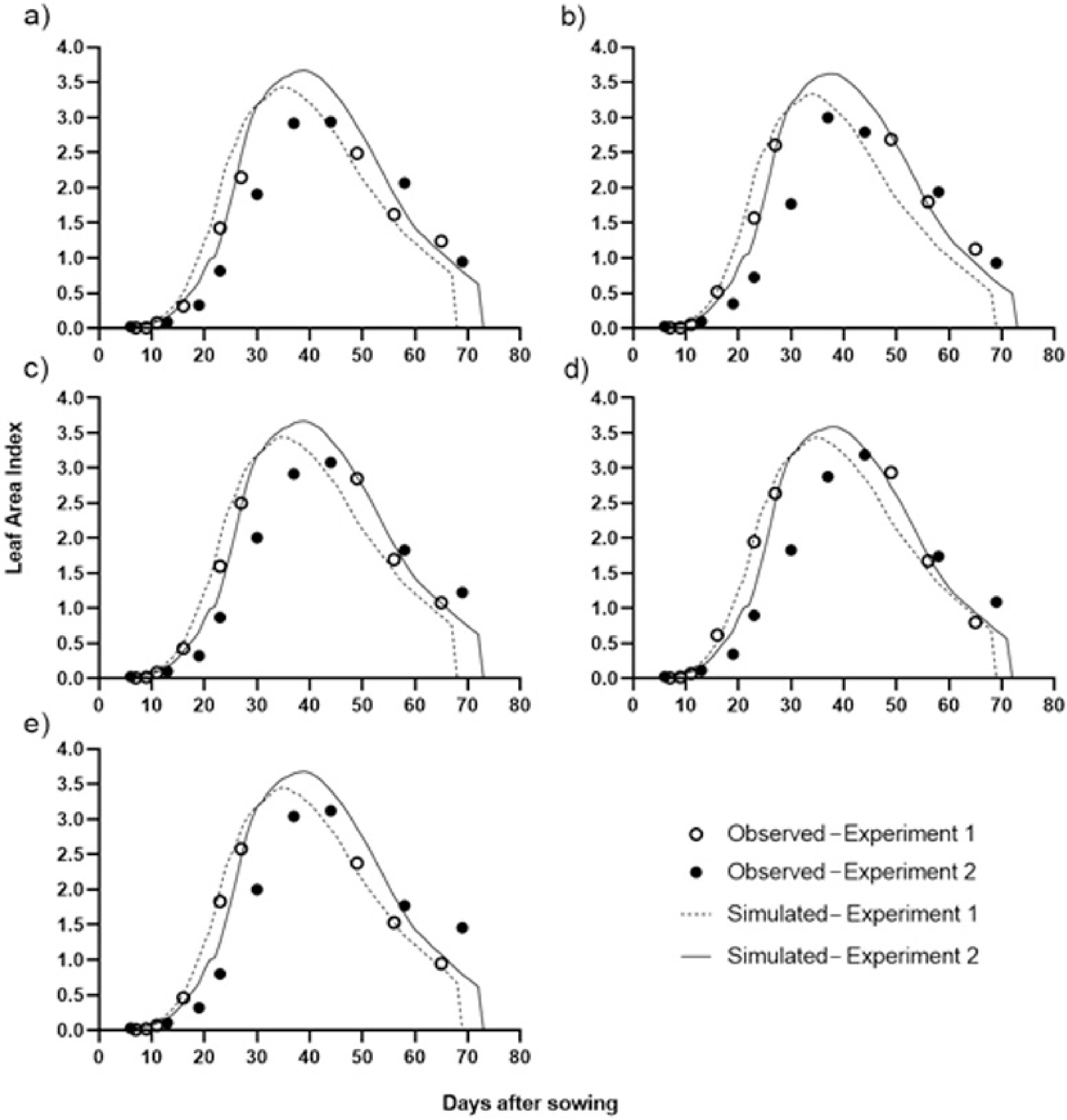

Figure 02: APSIM simulated and observed leaf area index development of five Proso millet accessions (a. L_1, b. L_11, c. L_12, d. L_14, e. L_25) from sowing (days after sowing (DAS)) of experiment 1 (2016–dry condition) and 2 (2017–rainy condition).

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

$$f_{in} = f_j\left(\frac{k_j LAI_{jn}}{k_j(LAI_{j1} + \cdots + LAI_{jn})}\right) \quad (12)$$

Experimental results: The observed biomass accumulation in five tested Proso millet accessions showed a similar pattern in both experiments (Figure 03). The observed biomass 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}) followed by experiment 2 (7288 kg ha^{-1}). The highest observed biomass of experiment 1 and 2 were from L_11 (7461 kg ha^{-1}) and L_25 (7735 kg ha^{-1}) respectively.

According to the student's t-test, the observed and simulated biomass were not significantly different ($p > 0.05$) in all five accessions. 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}) was 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}) was the poorest.

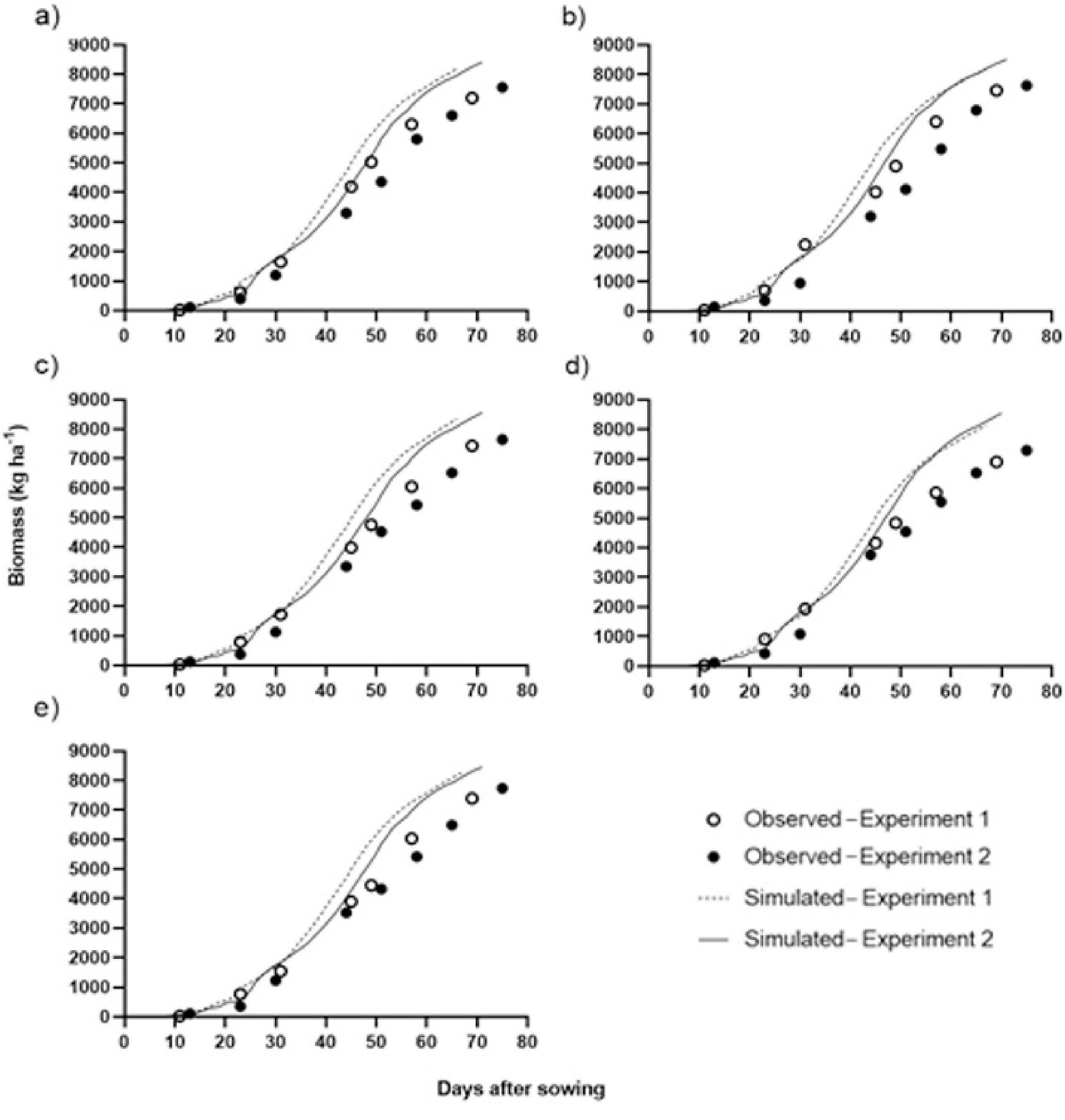

Figure 03: **APSIM simulated and observed biomass accumulation of five Proso millet accessions (a. L_1, b. L_11, c. L_12, d. L_14, e. L_25) from sowing (days after sowing (DAS)) of experiment 1 (2016–dry) and 2 (2017–rainy).**

Grain yield - model description: In the APSIM millet model, the partitioning of biomass among plant parts differs with growth stages. Only stems and flowers grow between flag leaf and start of grain filling stages, while 19% of dry matter production is allocated to flowers. 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 rate of dry matter accumulation between flag leaf and start of grain filling stages. The rate of grain growth is a genotype specific parameter which can be limited by temperature and drought stress (van Oosterom *et al.,* 2002).

Experimental results: APSIM simulation results of five Proso millet accessions are shown in Figure 04. 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). A good fit between observed and simulated yield was recorded in all the accessions and none of them was significantly different ($p > 0.05$).

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 35 farm fields with seven fields for each accession. The percentage yield change after calibration of the APSIM millet model was initially evaluated. After the calibration using accession specific parameters, the yields of all the accessions increased when compared with the Pearl millet cultivar hhb67 (the cultivar used as the base in the calibration) under similar climate, soil and crop management practices. The yield increment after the calibration ranged from 15.2% (L_1, RMSE 194 kg ha^{-1}) to 46.5% (L_25, RMSE 546 kg ha^{-1}).

The slope of the regression line (0.41) of observed and simulated yield for all the accessions was significantly ($p < 0.05$) different from zero. Accessions L_14 (RMSE 174 kg ha^{-1}) and L_1 (RMSE 386 kg ha^{-1}) showed the highest and the lowest agreement between observed and simulated yields respectively. The lowest and the highest observed mean yields of accessions were from L_11 (987 ± 224kg ha^{-1}) and L_25 (1556 ± 347 kg ha^{-1}) respectively. Similarly, in simulations, L_11 recorded the lowest yield (1080 ± 270 kg ha^{-1}) while the highest yield was from L_25 (1499 ± 192 kg ha^{-1}).

Most of the low yielding fields (less than 1000 kg ha^{-1}) showed overestimations (Figure 05a). The observed yields (1187±336 kg ha^{-1}) of tested 35 fields showed a significantly ($p < 0.05$) positive correlation ($r=0.54$) with the simulated yields (1208±255 kg ha^{-1}, RMSE 289 kg ha^{-1}). The index of agreement of yield was 0.68 suggesting a good agreement between observed and simulated yields. Therefore, the Proso millet yield of accessions collected from farmer fields in Sri Lanka can be explained by the calibrated APSIM millet model (Figure 05a). It should be noted that the observed data were originated from the fields where crops were grown 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. This also was expected as crops in farmers' fields tend to suffer from different stresses such as weeds, attacks from higher pests as elephants, peacocks and wild boars.

The probability exceedance distribution pattern for yield data was not separated according to the median values in both observed (1214 kg ha^{-1}) and APSIM simulated (1115 kg ha^{-1}) yields (Figure 05b). The yields ranged from 470 kg ha^{-1} to 1956 kg ha^{-1} in observed fields. In APSIM simulated fields, the values ranged from 848 kg ha^{-1} to 1628 kg ha^{-1}.

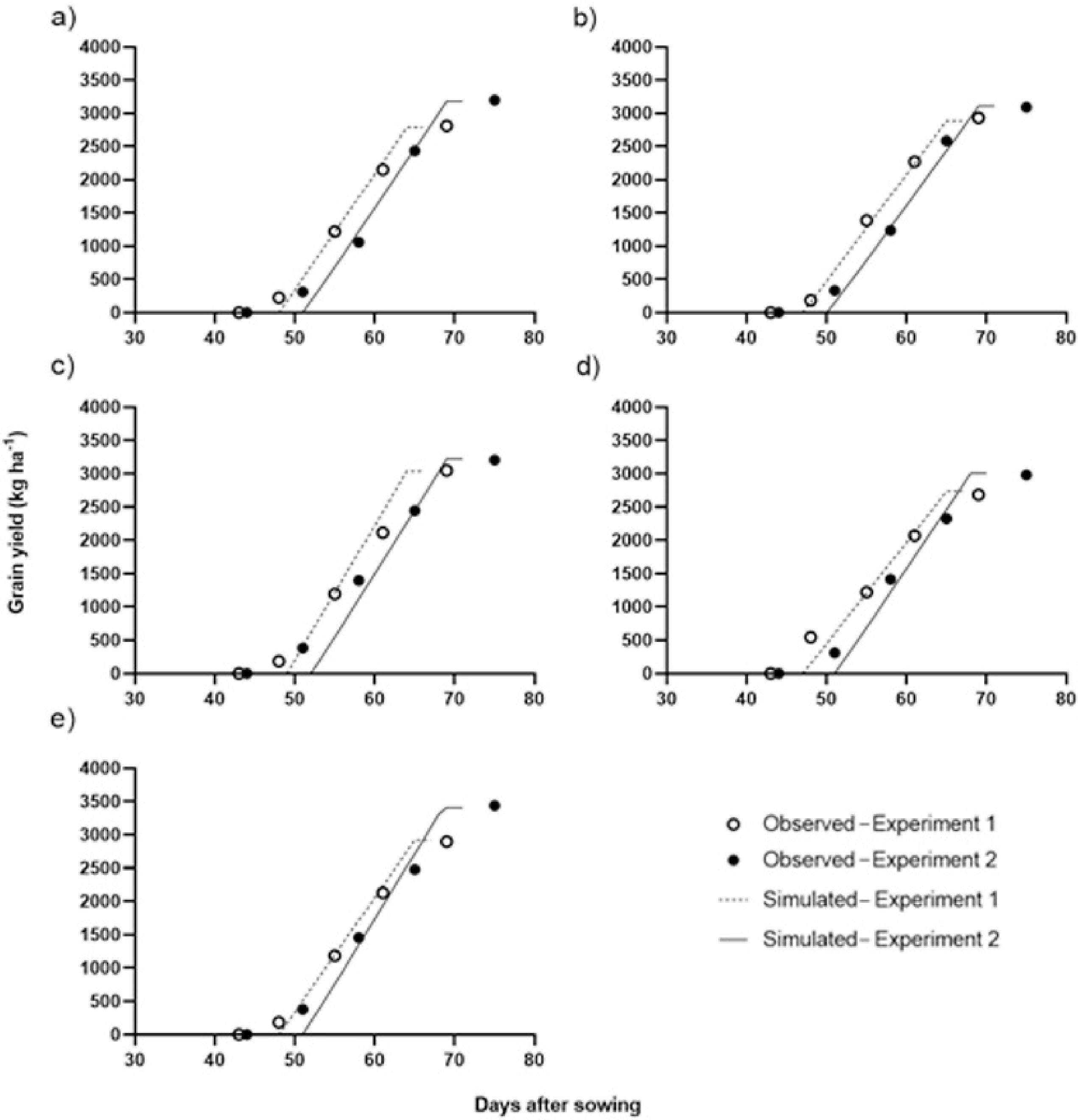

Figure 04: APSIM simulated and observed biomass partitioning to grains of five Proso millet accessions (a. L_1, b. L_11, c. L_12, d. L_14, e. L_25) from sowing (days after sowing (DAS)) of experiment 1 (2016–dry) and 2 (2017–rainy).

Model Applications

The simulated yields in the farmers' fields (Figure 05) were not as high as the values for the model calibration (Figure 04), indicating that the crops were grown under stress conditions in the farmers' fields. Therefore, the calibrated model was used as below to simulate the (i) plant extractable soil water content and (ii) the sensitivity of nitrogen fertiliser, which were two possible reasons to lower yields.

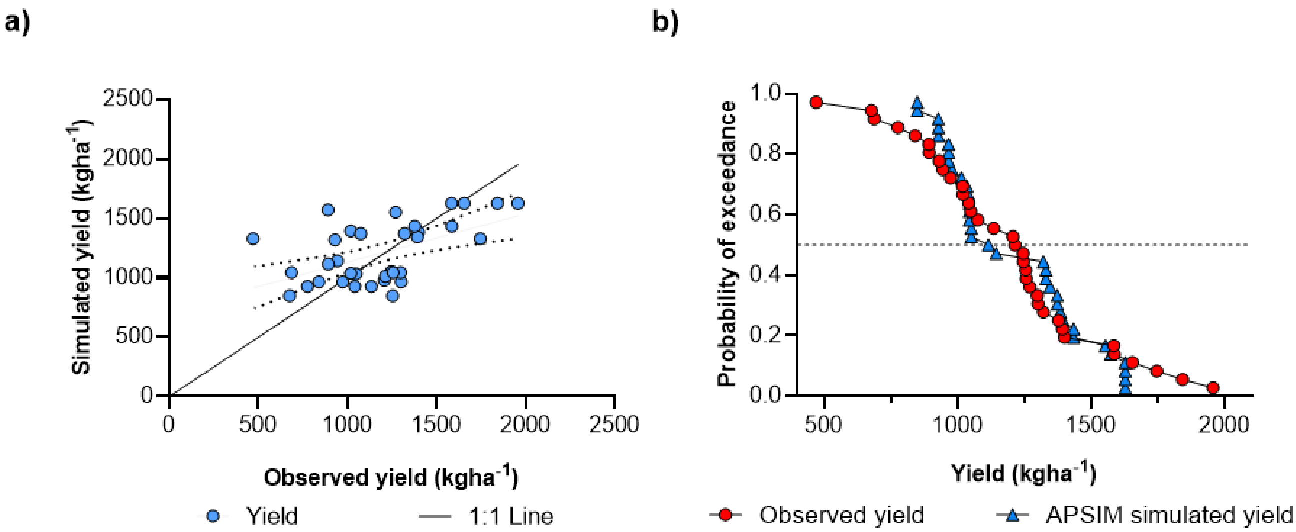

Figure 05: **a) Observed and APSIM simulated yields and b) the probability of exceedance of five Proso millet accessions for farmer fields in Bodagama Sri Lanka during 2015 growing season (n=35). The 95% confidence interval of the linear regression is marked in the dotted line.**

Simulated soil water content and grain yield: Soil water supply is one of the functions that determine daily biomass accumulation (Equation 10). Therefore, APSIM simulated extractable soil water content relative to the lower limit at 15 bars pressure (ESW) was plotted against DAS to study the variation of soil water and moisture stress. Three accessions were selected under farm field conditions and compared with L_1 under experimental conditions (experiment 2) (Figure 06). The accessions from farmers' fields were selected as; the field with the lowest (L_2) and the highest (L_36) simulated yield and the field with close to the mean yield (L_27) in the study area.

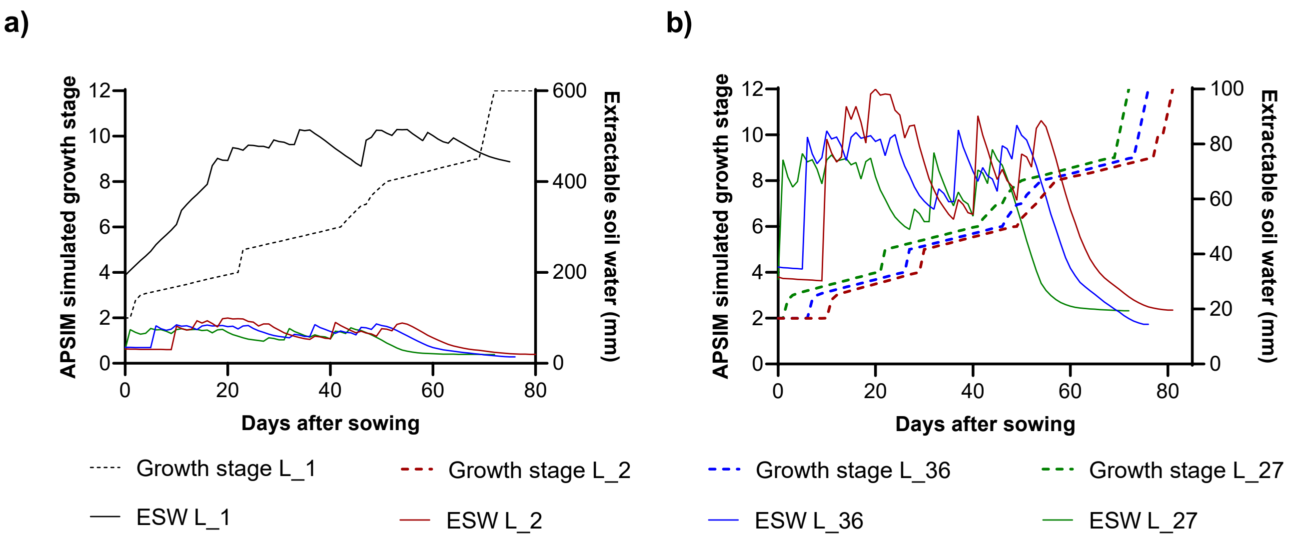

Figure 06: **Comparison of APSIM simulated growth stage and extractable soil water relative to LL15 (ESW) at (a) Sabaragamuwa University of Sri Lanka (SUSL - L_1) and selected farmers' fields (L_2, L_36 and L_27) and (b) farmers' fields (except SUSL).**

APSIM simulated ESW in the experimental field was few times higher than the ESW in farmers' fields for all the accessions (Figure 06a). Also, comparatively higher fluctuations of ESW were observed in the farmers' fields (Figure 06b). The ESW reduced from 70 to 20 mm from the start of grain filling (growth stage 8, 50 – 57 DAS) to harvesting stages (growth stage 12, 72 – 81 DAS) in all three fields (Figure 06b). Therefore, low ESW during the whole cropping season and very low ESW during the critical growth stage (grain filling) can be suggested as the reason for lower yields in farmers' fields.

Sensitivity of grain yield to nitrogen application: Most of the farmers (94%) used in the model validation did not use fertilisers for Proso millet fields, and therefore, low nutrient availability can be suggested as another reason for lower yields. The response of grain yield to N as basal fertiliser (urea 125 kg ha^{-1} at planting as recommended by DOASL) was studied using the calibrated model. The yield significantly ($p < 0.05$) increased after application of basal fertiliser in Proso millet fields. The fertiliser application increased the yield by 50.2±32.7%. A significantly ($p < 0.05$) higher response to N fertiliser was reported from L_11 with a yield increment of 92.9±47.5%. However, the yield increment was not significantly different ($p > 0.05$) among 4 other accessions. Low nitrogen content is another reason for lower yields in the farmer fields and fertiliser application is a good adaptation strategy to increase Proso millet yield in the study area.

DISCUSSION

APSIM millet model has been adapted from the Pearl millet model, 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 results of the first attempt to test APSIM millet model for Proso millet.

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 on the identification of the tested accessions. A good agreement between observed and calibrated LAI, biomass and yield in experiment 1 (dry season) suggests the drought favourable characteristics of Proso millet accessions. However, the adaptation of each accession or seed source to a given agro-ecological 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).

The five tested Proso millet accessions 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. However, 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 (Wimalasiri *et al.,* 2017). Therefore, further modelling approaches are needed to study the impact 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.

A lower plant density (20 plants m^{-2}) was used in model validation because the APSIM millet was not parameterized for higher plant densities. Previous APSIM simulations on maize revealed that increment of plant density significantly ($p < 0.05$) decreased both grain yield and water use efficiency under drier conditions (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 (Ren *et al.,* 2016). 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.

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. The increment of plant density decreases the Y_0 (up to the 12 plants m^{-2}) therefore, reduces the LAI (van Oosterom, Carberry, and O'Leary, 2001). 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 due to the increased LAI of upper leaves. This will increase interplant competition that leads to tiller death (van Oosterom *et al.,* 2001b). Death of tillers reduce the total biomass of the millet plant and can be suggested as 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 03). Biomass accumulation is a function of RUE (Equation 11), therefore, incorrect RUE values lead to inaccurate simulations. The RUE originally quantified for Pearl millet was used in the model as, 0 in stage 1,2, 11 and 12, 2.17 g MJ^{-1} in stages 3–7 and 1.6 g MJ^{-1} in stages 8-10 (van Oosterom *et al.*, 2002). Due to the lack of data on RUE of Proso millet, RUE value of Sorghum (3.2 g MJ^{-1}) which was comparatively higher was used in previous modelling attempts of Proso millet (Saseendran *et al.,* 2009). Therefore, the values for Pearl millet in the existing millet model (van Oosterom *et al.,* 2002) were used in the simulation in this study. However, it was reported that the mean RUE of Proso millet (1.43 g MJ^{-1}) was lower than the Pearl millet (1.83 g MJ^{-1}) (Kamkar *et al*., 2005). The RUE of the Proso millet accessions collected from farmers' fields could be lower than that for Proso millet varieties (Kamkar *et al.,* 2005; Saseendran *et al.,* 2009) 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 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 12) is high due to the higher LAI which was overestimated at the vegetative stage up to the maximum LAI on around 40 DAS (Figure 02). Therefore, further calibration of the model for LAI (Equation 5) using the accession specific data is needed as described previously.

No attempt has been made here to study the effects of differences in the Proso millet plant density in the experimental and farmer fields. Therefore, detailed field experiments with different plant densities are needed to understand the effect of plant density on the yield. The calibrated and validated model can be used for several purposes including the impact of crop management practices and soil properties on growth and development, water relationships, adaptation measures, climate sensitivity studies and yield projections that will assist in decision making towards the popularisation of this underutilised crop. Also, the same procedure can be adapted for other neglected crops that show a potential to diversify conventional farming systems under climate change.

CONCLUSIONS

The results of the current study show the performance of APSIM millet model for simulating five Proso millet accessions grown under rain-fed conditions with low inputs. Genetic coefficients derived for the APSIM millet model were successfully used to simulate Proso millet production. Crop phenology, leaf area index, biomass and grain yield recorded a good agreement between observed and simulated values suggesting a good calibration of genetic coefficients for the millet module of APSIM. The simulated yield from the calibrated model showed a significant ($p < 0.05$) correlation with the yields observed in 35 farmers' fields. Therefore, the APSIM millet model is a suitable candidate to simulate Proso millet yield in Sri Lanka and has the potential to be used for different purposes such as studies on climate sensitivity, yield projections and growth and development under different crop management practices. Identification of knowledge gaps for precise Proso millet modelling in tropical environments which is important in diversification of traditional farming systems were initiated by this calibration exercise.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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