

Development and Validation of a Model to Simulate Phenology, Canopy Growth and Yield of Maize, Mungbean and Tomato under Tropical Farming Systems

J.B.D.A.P. Kumara^{1,2*}, L.D.B. Suriyagoda³, W.A.J.M. De Costa³, M.A.P.W.K. Malaviarachchi^{1,4}, K.M.R.D. Abhayapala¹ and R.M.S. Fonseka³

¹Postgraduate Institute of Agriculture, University of Peradeniya, Peradeniya, 20400, Sri Lanka

²Department of Export Agriculture, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya, 70140, Sri Lanka

³Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, 20400, Sri Lanka

⁴Field Crops Research and Development Institute, Mahalluppallama, 50270, Sri Lanka

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Kumara, J.B.D.A.P. 
<https://orcid.org/0000-0003-1176-1246>

ABSTRACT

A significant portion of crop production in the tropics occurs at subsistence level with high vulnerability to climate change. Process-based crop simulation models are effective tools to predict environmental impacts, including climate change effects, and make management decisions on crop production. The principal objective of this work was to develop crop-specific simulation models to predict phenology, canopy growth, and yield performance of maize, mungbean, and tomato crops grown in the tropics, with special relevance to locally adapted inbred germplasm. The developed models consisted of sub-models to simulate canopy growth, radiation interception and conversion, and dry matter partitioning. All sub-models were parameterized by detailed measurements of leaf growth, dry matter accumulation, and partitioning on locally adapted varieties of the three crops over two cropping seasons. The same crop varieties were established in a multi-locational field experiment spanning a sufficiently wide temperature gradient over four cropping seasons for model validation. Models were validated by comparing model predictions of phenological development and yield against field observations and additional secondary data from the literature. Overall, simulated phenological development ($R^2 > 0.5$, $RMSE < 5$ days for all three crops) and yield ($R^2 > 0.5$, $RMSE < 68, 48$ and 476 g/m² for maize, mungbean, and tomato, respectively) of the three crops were in agreement with the observed data under a wide range of environmental conditions. These modelling approaches can be successfully applied to open-pollinated (maize) and inbred varieties (mungbean and tomato) growing under the farmer fields in tropical South Asia.

* Corresponding author- arunajbd@agri.sab.ac.lk

INTRODUCTION

Agriculture in developing countries is characterized by growing crops with limited inputs, consumption of produce within the farm household, and selling the surplus (Morton, 2007). Often, in this region fertilizers are provided at a subsidized rate and irrigation is provided free of charge (FAO, 2011). Crop cultivation under these conditions is unique in comparison to commercial, large-scale farming in developed countries.

Crop growth simulation models can be used to determine the actual and potential yield of crops in a wide range of climates, soils, and management regimes. Validated models enable the prediction of impacts of a range of abiotic and biotic factors and allow the evaluation of different adaptation and management strategies. Several widely used cropping system models (for example, DSSAT and APSIM) have been adapted for globally important crops (for example, rice, wheat, maize, and soybean).

However, there are several constraints that have limited the use of cropping system models (CSMs), especially by researchers and growers involved in tropical conditions. A major constraint is the unavailability of data of adequate quality and comprehensiveness (Jones *et al.*, 2017), especially in the tropics, for parameterization and validation of CSMs, which depend on a complete set of climatic and phenological data for accurate performance (Kephe *et al.*, 2021). Prediction of crop performance using available CSMs requires not only a model that predicts potential production (*i.e.*, crop yields in the absence of abiotic and biotic stresses), but also sub-models that quantify yield reductions due to biotic (*e.g.*, pests, diseases, and weeds) and abiotic (*e.g.*, water and nutrients) limitations. The sub-models, which incorporate water and nutrient limitations, involve modelling of complex soil processes involving water, nutrient, and carbon dynamics (Jones *et al.*, 2017). The substantial research effort to parameterize these sub-models and the greater data requirements push the CSMs beyond the available infrastructure capacity among potential users

(*i.e.*, researchers, managers, and policymakers) in tropical farming. This highlights the need for in-country development of locally relevant and applicable models, with a lower research effort and data requirements to parameterize and operationalize. Furthermore, it is acknowledged that modelling the effects of biotic stresses has lagged behind that of other factors in existing CSMs (Jones *et al.*, 2017). Moreover, actual yields of the wide range of crops in the tropics are determined by a variety of management options adopted by farmers to overcome abiotic and biotic stresses (*e.g.*, different irrigation and fertilizer application options, and resistant varieties). Therefore, a research effort to develop locally-relevant crop models from first principles and parameterize local germplasm in local farming systems would be more useful than a similar effort to parameterize an existing CSM.

In-country development of crop models not only develops expertise among local researchers but also makes it easier to transfer these models and their outputs to end-users (*i.e.*, crop managers and policymakers). In the long run, the effort invested in developing local models from first principles empowers the local researchers to improve them by incorporating sub-models to model country-specific constraints (*e.g.*, air pollutants, soil limitations and toxicities, pests, diseases, and weeds, and land-use change) as well as globally-relevant constraints (*e.g.*, climate change, drought, and heat stress) in accordance with the prevailing levels of data availability and resources for parameterization. This would not be possible with globally available CSMs as their source codes are not available to local researchers.

The principal objective of this work was to develop crop-specific simulation models to predict phenology, canopy growth, and yield of maize (*Zea mays* L.), mungbean (*Vigna radiata* L.) and tomato (*Lycopersicon esculentum* L.) grown in tropical farming conditions, with special relevance to locally-adapted open-pollinated and inbred germplasm in Sri Lanka. The long-term objective of this in-country modelling effort is to use these models to predict the impacts of

climate change on these crops and to evaluate different adaptation options. Several widely used simulation models are available for maize (Lukeba et al., 2013); however, fewer are available for mungbean and tomato (Chauhan et al., 2010; Boote et al., 2012; Lukeba et al., 2013). From the conceptual frameworks of these models, we have opted to develop a new set of models for the reasons outlined earlier.

MATERIALS AND METHODS

Description of the model

The simulation models for all three crops had a similar framework (Figure S1). All processes were simulated assuming crop growth and development without water and nutrient limitations and biotic stresses (*i.e.*, pests, diseases, and weeds). The models were driven by meteorological data with a daily time step. Time courses of canopy leaf area index (LAI) were estimated by simulating leaf initiation, expansion, and senescence based on cumulative thermal time (CTT, °C days). Simulated LAI drove radiation interception while CTT-driven radiation-use efficiency (RUE) simulated the time courses of biomass accumulation. Partitioning of biomass to roots, stems, leaves, and harvested organs was simulated based on CTT-driven partitioning coefficients.

Model parameterization

Parameterization of the model was done by taking measurements in a series of maize, mungbean and tomato crops grown in a multi-locational field experiment conducted during 2012-2014 in four consecutive cropping seasons at four locations in Sri Lanka (Table S1), representing different agro-climatic zones along an increasing mean seasonal temperature gradient from 20 °C to 28 °C. Planting and harvesting dates, crop management, meteorological and soil characteristics of those locations and seasons are given in Malaviarachchi et al. (2015) and Abhayapala et al. (2018). Locally-adapted inbred varieties of maize, mungbean, and tomato; *Ruwan*, *MI-6* and *Thillina*, respectively, were grown in 5 m × 5 m plots with three replicates and managed with the

standard management practices which ensured the absence of water and nutrient limitation and biotic stresses.

Data obtained from Kundasale during the first two seasons (2012/2013 Maha and 2013 Yala) were used for estimation of model parameters (Table S1). Data obtained from the 3rd and 4th seasons from Kundasale, all four seasons from other locations (Rahangala, Mahailuppallama, and Kilinochchi), and secondary data from the National Coordinated Varietal Trials (Department of Agriculture, Sri Lanka) were used for model validation.

Weather data

Weather data at canopy height (1.5 m) were collected at 60-minute intervals using on-site automated weather stations (Watch Dog, 2000 series, Spectrum Technologies, Inc., USA). Daily values of solar radiation (MJm⁻²d⁻¹) and temperature (°C) were used in simulations.

Phenology and leaf growth

Days (*t*) required for seedling emergence (for direct-seeded maize and mungbean), successive main stem leaf initiation, flowering/tasselling, silking/fruit setting, and physiological maturity were recorded. The development cycle of each crop was divided into two phases; vegetative phase from seedling emergence (EM) or transplanting to silking (SI) or flowering (FL), and the reproductive phase from SI or FL to physiological maturity (PM). Area per leaf at different positions were measured non-destructively. Dead leaves were identified when 50% of its area changed from green to yellow.

Literature based cardinal temperatures were used to calculate cumulative thermal time (CTT) to simulate the phenological development of all three crops. Base temperatures of 8, 5 and 7 °C and optimal temperatures of 30, 29 and 27 °C were used for maize, mungbean, and tomato, respectively (Jones et al., 1991; Birch et al., 1998; Robertson et al., 2002; Padilla and Otegui, 2005; Chauhan et al., 2010; Boote et

al., 2012). Moreover, 40 °C was considered the maximum temperature for all the crops. Leaf area development was simulated as the combination of: (a) rate of leaf emergence; (b) rate and duration of expansion of individual leaves; and (c) their longevity (Marcelis et al., 1998).

Leaf initiation

The total number of leaf tips appearing from seedling emergence was regressed against CTT (Eq. 1). The regression slope was considered as the rate of leaf initiation.

$$LNO=(a \times CTT)+b \dots\dots\dots(1)$$

where LNO is the total number of main stem leaves, *a* the phyllochron (i.e., the time gap between two successive leaf initiations) and *b* the number of leaves at transplanting.

Individual leaf area

Individual leaf area at different leaf positions (*LA*) was measured and regressed against leaf position. Main stem *LA* of maize and mungbean showed a typical bell-shaped pattern following the Gaussian model (Eq. 2) whereas that for tomato followed a second order polynomial (Eq. 3).

$$LA_n = a \exp \frac{-(LNO-b)^2}{(2 \times c^2)} \dots\dots\dots(2)$$

$$LA_n = (a \times LNO^2) + (b \times LNO) - c \dots\dots\dots(3)$$

where *LA_n* is leaf area at the *n*th leaf position, *LNO* is leaf position and *a*, *b*, and *c* are estimated parameters.

Leaf expansion duration

The thermal time required by each leaf to attain the full expansion from the appearance of leaf tip was considered the thermal duration for leaf expansion (*L_{exp}*). For tomato, *L_{exp}* was estimated after transplanting. The relationship between *LNO* and *L_{exp}* was linear for tomato (Eq. 4).

$$L_{exp} = (a' \times LNO) + b' \dots\dots\dots(4)$$

Leaf expansion durations of maize and mungbean were computed by a second-order polynomial functions of *LNO* computed *L_{exp}* of maize and tomato (Eq. 5).

$$L_{exp} = (a' \times LNO^2) + (b' \times LNO) + c' \dots\dots\dots(5)$$

Where, *a'*, *b'* and *c'* are crop-specific parameters.

Based on computed *L_{exp}* (Eqs. 4 and 5), the respective thermal durations for leaf expansion were computed as the thermal times required from the appearance of each leaf tip to full expansion.

Leaf expansion rate

Leaf expansion rate (*LER*) was calculated as the ratio between fully expanded leaf area at each leaf position and *L_{exp}*. The resulting variation of *LER* with leaf position was described by Gaussian (Eq. 6), second-order polynomial (Eq. 7), and negative-linear (Eq. 8) relationships for maize, mungbean, and tomato, respectively.

$$LER_n = a'' \exp \frac{-(LNO-b'')^2}{(2 \times c''^2)} \dots\dots\dots(6)$$

$$LER_n = a'' \times LNO^2 + b'' \times LNO + c'' \dots\dots\dots(7)$$

$$LER_n = (a'' \times LNO) + b'' \dots\dots\dots(8)$$

where *LER_n* is *LER* at *n*th leaf position and *a''*, *b''* and *c''* are crop-specific parameters.

Leaf senescence

Leaf senescence occurred in all three crops from the bottom upward. The senesced leaf area was calculated using observed senesced leaf numbers and their areas. Maize and tomato showed two phases of leaf senescence (pre- and post-tasselling/ flowering), which were simulated as linear functions of CTT as given in (Eqs. 9 and 10),

$$LAS_{PT} = (S_1 \times CTT) - S_2 \dots\dots\dots(9)$$

$$LAS_{PST} = (S_3 \times CTT) - S_4 \dots\dots\dots(10)$$

where LAS_{PT} and LAS_{PST} , respectively are pre- and post-tasselling/ flowering leaf area senesced, and S_1, S_2, S_3 and S_4 are crop-specific parameters.

Estimation of Specific Leaf Area (SLA)

Destructive plant samples from all leaf axes collected at the FL and PM stages were used to estimate SLA as the ratio of leaf area (LA) to leaf dry weight (LBM) (Eq. 11).

$$SLA = \frac{LA}{LBM} \dots\dots\dots(11)$$

Simulation of leaf area (LA) and LAI

Accumulation of leaf area is the sum of the products of leaf initiation (i.e., number of leaves) and leaf expansion (i.e. area of individual leaves). Leaf initiation is a temperature-dependent process, while leaf expansion depends on the thermal duration of leaf expansion, biomass production, and partitioning to leaves and SLA. Our models assume that all expanding leaves have an equal affinity for the available biomass produced on a given day and that all expanding leaves have an equal sink strength. Therefore, LA expansion in each leaf position is a function of daily biomass partitioned to leaves and SLA. Leaf area per plant (LA_{plt}) was simulated as the summation of LA at each leaf position. However, LA_{plt} is the balance between the accumulation and senescence of leaf area (LA_{sen}). Finally, LAI was simulated as the product of active leaf area and plant density ($pltden$) (Eq. 12). For LAI on n^{th} day,

$$LAI_n = (LA_{plt} - LA_{sen}) \times pltden \dots\dots\dots(12)$$

Simulation of light interception, radiation-use efficiency (RUE) and biomass accumulation

Daily biomass accumulation was simulated as the product of daily intercepted photosynthetically active radiation (PAR) and radiation-use efficiency (RUE). Daily intercepted PAR (I_i) was computed from incident PAR (I_0) using the Monsi and Saeki (1953) model (Eq. 13).

$$I_i = 1 - I_0 e^{(-k \times LAI)} \dots\dots\dots(13)$$

Values of 0.40, 0.30, and 0.75 were assigned for the light extinction coefficients (k) of maize, mungbean, and tomato, respectively (Gallo and Daugherty, 1986; Heuvelink, 1996; Chauhan et al., 2010).

The RUE was estimated by fitting a linear regression between crop growth rate (CGR- $g\ m^{-2}\ d^{-1}$) and the estimated rate of interception of PAR ($\Delta IPAR$ - $MJ\ m^{-2}\ d^{-1}$) for successive periods between destructive harvests. Repeated destructive harvests of all crops at Kundasale during the first two seasons were used to determine CGR (Eq. 14) while $\Delta IPAR$ was computed from daily I_i (Eq 15).

$$CGR = \frac{W_2 - W_1}{T_2 - T_1} \dots\dots\dots(14)$$

$$\Delta IPAR = \frac{IPAR_{t_2} - IPAR_{t_1}}{T_2 - T_1} \dots\dots\dots(15)$$

where W_2 and W_1 are field-measured dry weights at times T_2 and T_1 , and $IPAR_{t_2}$ and $IPAR_{t_1}$ are cumulative I_i (IPAR) at T_2 and T_1 , respectively.

Simulation of biomass partitioning

Biomass allocation coefficients (PC_x) were calculated for each organ based on the ratio of the absolute growth rate (i.e. increasing biomass per unit time) of an organ to the absolute growth rate of the total plant (Eq. 16). For this, the dry weights of organs were measured by independent destructive plant sampling.

$$PC_x = \frac{W'_{xt1} - W'_{xt-1}}{BM'_t - BM'_{t-1}} \dots\dots\dots(16)$$

where W'_{xt1} and W'_{xt-1} are the dry weights of a particular organ (e.g. leaves, stems, roots, or reproductive organs) measured at times t and $t-1$, respectively. BM'_t and BM'_{t-1} are the total biomass measured at times t and $t-1$,

respectively. The variation of PC_x with time was simulated by regressing PC_x against CTT.

Model development, validation, and analysis

All simulated crop processes were integrated into models within the common framework (Figure S1) in "R" version 2.15. (R Core Team, 2018). Model validation was performed using experimental data of this study, which were not used in model development (Table S1), and secondary data from the Department of Agriculture, Sri Lanka. Simulated days to flowering and yields were used for validation. The Goodness-of-fit of the models for observed and simulated data was tested by the paired sample *t*-test and Root Mean Square Error (RMSE).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Simulated - Observed)^2} \dots (17)$$

Where, *n* is the number of observations.

RESULTS & DISCUSSION

Based on the cardinal temperatures, the respective CTTs for 50% flowering in maize, mungbean, and tomato were 984 ± 43 , 652 ± 19 and 660 ± 17 °Cdays, respectively. The corresponding CTTs for crop maturity were 1835 ± 38 , 1140 ± 11 and 2019 ± 53 °Cdays, respectively.

Canopy development in maize, mungbean and tomato

Leaf appearance

Leaf appearance in all three crops was linearly related to cumulative thermal time (Figure S2). The mean maximum main stem leaf numbers of maize and mungbean were 21 ± 0.4 and 7.5 ± 0.83 , respectively, and the CTTs required were 920 and 762 °Cdays, respectively. Tomato contained 6-7 leaves in three-week old seedlings at transplanting. As leaf appearance of tomato continued until crop maturity, the maximum main stem leaf number depended on length of the cropping season. The thermal times between two successive leaf appearances were 43.4, 96.5 and 66.6 °Cdays for maize, mungbean, and tomato, respectively.

Individual leaf area

Area of individual leaves (LA) on main stems of maize, mungbean, and tomato increased until the 17th, 5th, and 19th leaf positions, respectively and then decreased (Figure 1). The respective maximum LA of maize, mungbean, and tomato were 765 ± 54 , 379 ± 38 , and 154.8 ± 8.5 cm²/leaf. The mean leaf area of a transplanted tomato seedling with 3-4 fully grown leaves and 2-3 expanding leaves was 35 ± 6 cm²/plant.

Leaf expansion

The time required for leaf expansion at each leaf position of maize increased from the first to the 13th leaf and then decreased (Figure 1). This relationship was best explained by a second-order polynomial. The rate of leaf expansion increased from the 1st to the 20th leaf (5 cm²/°Cday), then decreased to the flag leaf (Figure 1).

The time required for leaf expansion of mungbean increased until the appearance of the 6th leaf on the main stem and remained constant thereafter (Figure 1). The maximum duration for leaf expansion in mungbean was 160 ± 20 °Cdays. The rate of leaf expansion increased until the appearance of the 5th leaf (2.2 ± 0.2 cm²/°Cday) on the main stem, after which it decreased. A second-order polynomial explained this relationship (Figure 1). The time required for leaf expansion of tomato followed a linear trend with leaf position (Figure 1). The mean maximum leaf expansion duration achieved after the 25th leaf position on the main stem was 213 ± 20 °Cdays. The leaf expansion rate of tomato decreased linearly with the leaf position (Figure 1). Therefore, the highest leaf expansion rate observed at the 12th leaf position was 0.73 cm²/°Cday.

Leaf senescence

Senescence of maize leaves occurred both before and after tasselling (Figure 2). During the pre-tasselling phase, 6-8 leaves senesced from the base of maize plants, and those leaves had a shorter leaf age (555 ± 55 °Cdays). Post-tasselling leaf senescence was observed after 1200 °Cdays and the longevity of leaves

at this stage was higher (1169±29 °Cdays) than that during pre-tasselling. The post-tasselling leaf area senescence rate (cm² [°C day]⁻¹) was higher than the pre-tasselling rate due to the larger leaves senescing at this stage. The LAI of mungbean was independent

of leaf senescence under recommended crop management because senescence was not observed until maturity. In tomato, senesced leaf area increased linearly with CTT (Figure 2). Post-flowering leaf area senescence rate was greater than the pre-flowering

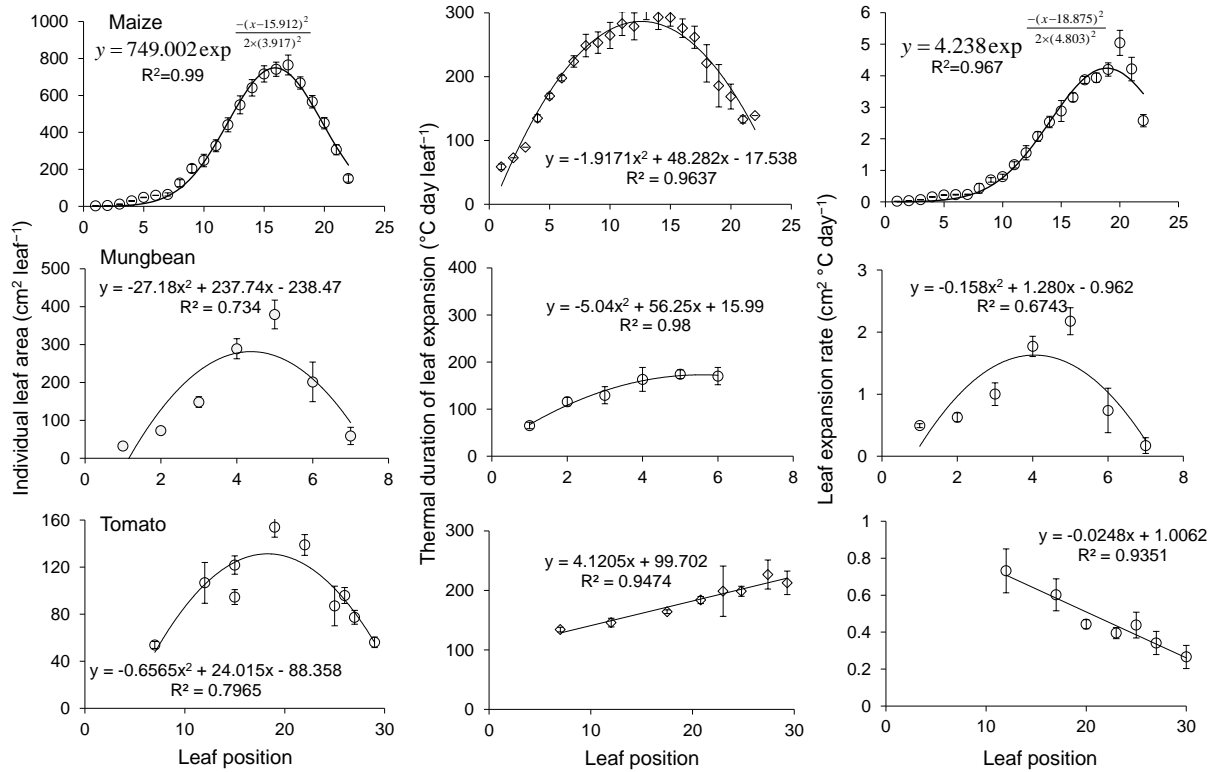


Figure 1: Relationships between leaf position on the main stem, and individual leaf area, thermal duration of leaf expansion and leaf expansion rate in maize, mungbean, and tomato (mean± standard error, n=12).

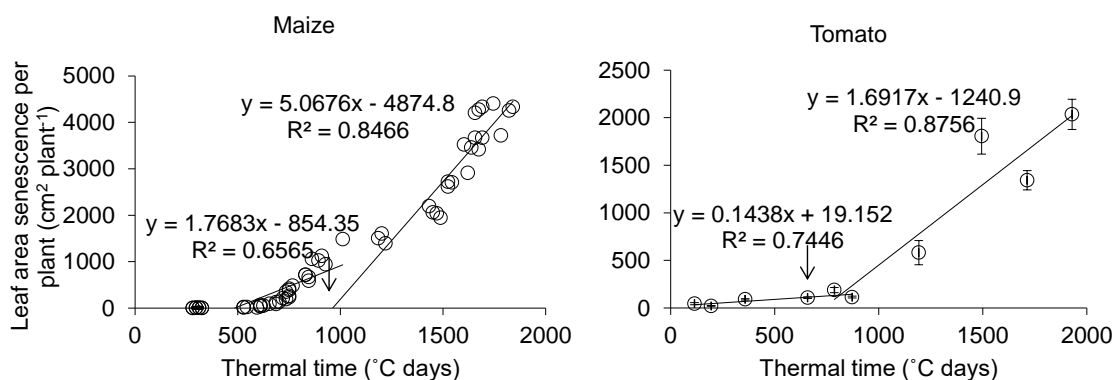


Figure 2: Relationships between the cumulative thermal time, and leaf senescence of maize and tomato. Two phases of leaf senescence represent leaves senesced before and after tasselling/flowering. Arrow indicates the time of tasselling. Data were collected from the crops cultivated under recommended management in the first and second seasons at Kundasale (mean ± standard error, n=4).

Radiation-use efficiency, biomass accumulation and partitioning

Among the three crops, the highest RUE was observed in maize (2.48 g/MJ¹ (PAR)) and the lowest in tomato (0.72 g/MJ¹), with mungbean having an intermediate RUE of 1.51 g/MJ¹ (Figure S3).

Maize leaves acquired nearly 60% of the daily biomass produced soon after germination, which gradually decreased to 40% at

tasselling (Figure 3), with further reductions towards physiological maturity. After germination, 20% of the daily biomass was partitioned to the pseudo-stem of maize, which increased until tasselling and then declined. After germination, nearly 20% of biomass was partitioned to roots, which decreased as crop growth progressed. Biomass partitioned to reproductive organs commenced at 950 °Cdays and increased sharply during grain filling.

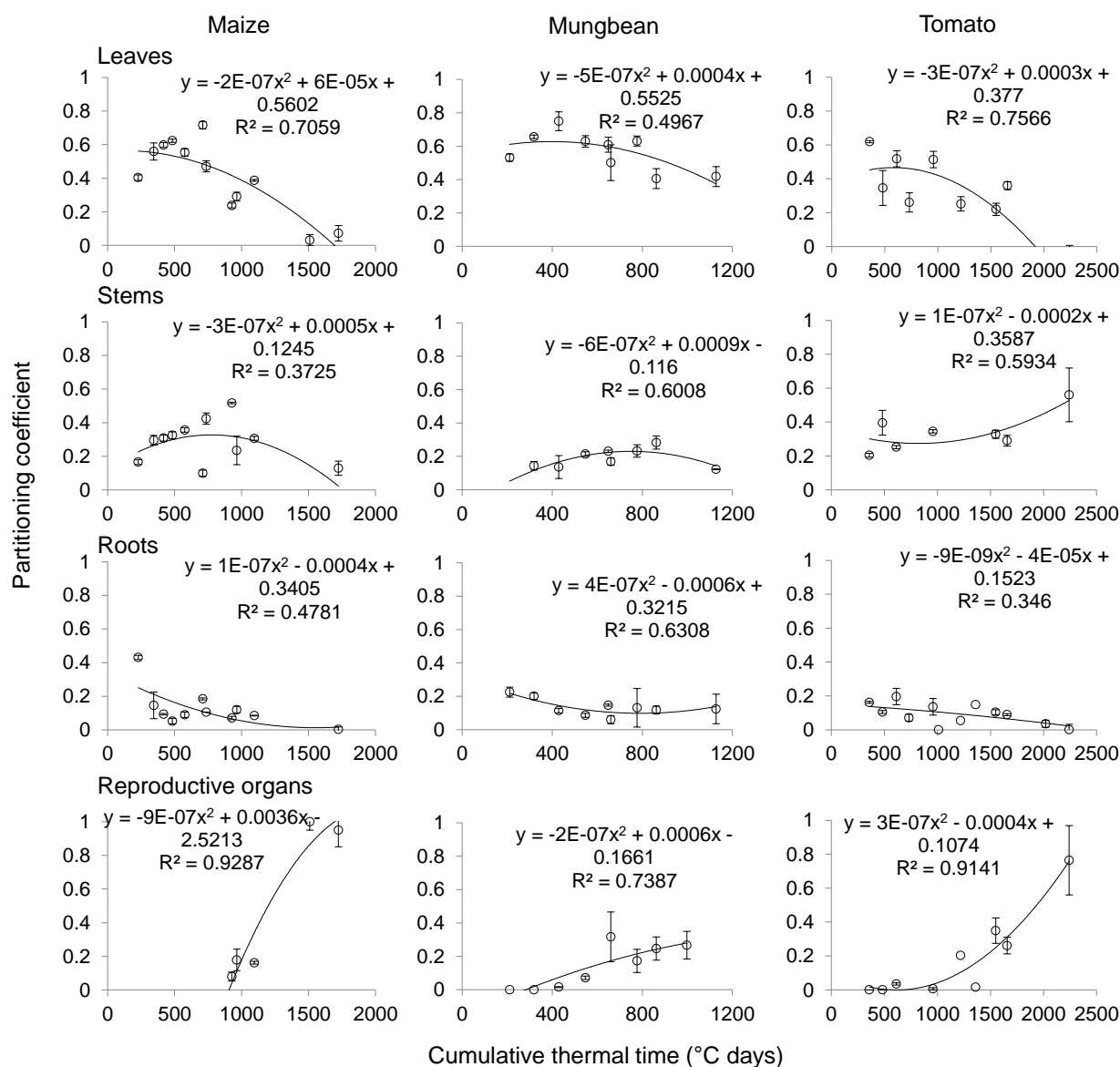


Figure 3: Relationships between the cumulative thermal time and partitioning coefficients of maize, mungbean and tomato to leaves, stems, roots and reproductive organs. The arrow indicates the time of tasselling/flowering (mean \pm standard error, n=3).

Mungbean leaves acquired 50-60% of the biomass produced until 600 °Cdays from germination, which gradually decreased towards physiological maturity (Figure 3). In contrast, stems of mungbean acquired 13-14% of biomass after germination, which gradually increased to 20-23% by 600 °Cdays and remained constant during seed filling. Roots acquired 20-22% of biomass after germination, which gradually decreased as crop growth progressed. Allocation of biomass to reproductive organs commenced after 400 °Cdays and increased during grain filling to achieve its potential maximum (*i.e.* 25-30%).

Tomato leaves acquired 50-60% of biomass after transplanting, which decreased after 1000 °Cdays (Figure 3). After transplanting, 20-25% of biomass was partitioned to stems, which increased as crop growth progressed. Roots acquired 10-20% of biomass after transplanting, which decreased after 1000 °Cdays. Biomass partitioned to reproductive organs increased continuously after 1000°Cdays.

Validation of models

The slopes of fitted regressions between simulated and observed days to flowering for maize, mungbean, and tomato were 0.996, 1.013 and 1.003, respectively, with calculated RMSE being 3.7, 1.7 and 2.8 days (Figure 4). The probability values for the null hypothesis of the paired sample *t*-test for maize, mungbean and tomato were 0.76, 0.09 and 0.52, respectively. Furthermore, correlation coefficients between simulated and observed days to flowering for the three crops were 0.83, 0.80 and 0.82, respectively. The slopes of regressions between the simulated and observed yields of maize, mungbean, and tomato were 0.98, 0.89 and 0.93, respectively (Figure 4). Calculated RMSE values for the three crops were 71.7 (13.7%), 27.9 (12.1%) and 475.5 (21.6%) g m⁻², respectively. Moreover, *P* values of the paired sample *t*-test for maize, mungbean, and tomato were 0.19, 0.18, and 0.12, respectively. Similarly, correlation coefficients between simulated and observed yields of the three crops were 0.80, 0.91 and 0.82, respectively. Therefore, models predicted the number of days to flowering and yields of all crops with acceptable accuracy.

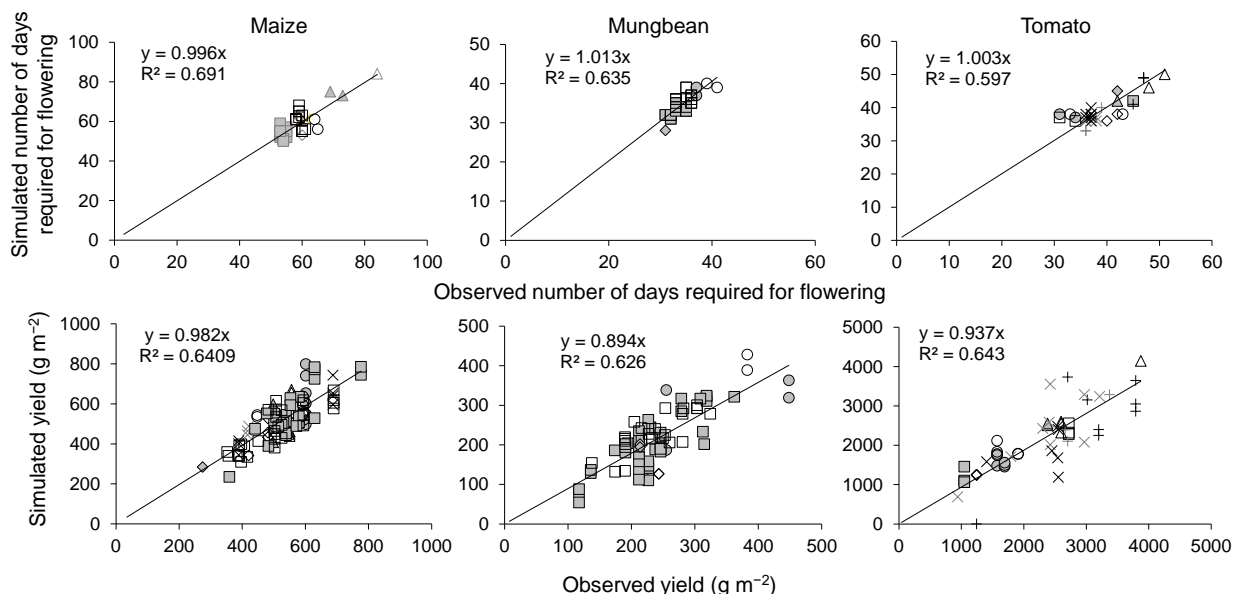


Figure 4: Relationships between the observed and simulated number of days required for flowering (upper panel) and yield (lower panel) of maize, mungbean, and tomato. Observed data were collected from the crops grown at Rahangala (triangle), Kundasale (circle), Kandy (X), Mahailuppallama (square) and Killinochchi (diamond). Maize cultivars were Ruwan, Sampath, Pacific and MI-MZ1 (n=97). Mungbean cultivars were MI-6, MI-5 and Ari (n=56). Tomato cultivars were Thillina, Bathiya, Rajitha, Larissa, Kallisto, Ceres and Pathma (n=46).

DISCUSSION

Performance of the locally-developed models and potential for development of extensions

The performance of the relatively simple models in the present work demonstrates the utility of in-country modelling efforts as an alternative to parameterization and use of globally available CSMs. Our models predicted the flowering phenology and yields of three important crops in tropical farming systems, not only in well-managed experimental fields in specific locations but also in national coordinated variety trials (NCVTs) conducted across a wide-range of farming environments. As NCVTs include several promising varieties which were being tested for environmental adaptation, acceptable predictions of phenology and yields by our models provide strong evidence of their robustness across local germplasm, which includes inbred and open-pollinated varieties. Therefore, these models form the foundation for a substantial effort to model crop performance when water and nutrients are limited. This will be done using the local expertise developed in this exercise, taking in to consideration the limited data availability and capability for parameterization. Given the complexity of crop-soil processes involved in parameterizing the relevant sub-models of CSMs, development of simpler sub-models as extensions to our models will be a more viable option in terms of both model development and their subsequent use by end-users.

Comparison of predictions of different crop processes by models of this work and those from cropping-system models

Predictions of the rates of different crop processes from simpler models of this work showed agreement with corresponding literature reported predictions from more comprehensive CSMs. However, there were a few disagreements as well. While the broad agreement justifies the use of simpler models, the disagreements highlight the need for parameterizing them based on local germplasm under local farming conditions. For example, there was agreement for 50%

flowering in all three crops and in the CTT for maturity in maize and mungbean. However, the CTT for maturity of tomato in this study was greater than the corresponding CTT from literature (Table 1). Similarly, initiation of new leaves on the main stem of maize, mungbean, and tomato in our work was linearly related to temperature and is in agreement with previous findings (Table 1). Leaf initiation rates of mungbean observed in this study and those reported in the literature are in close agreement (Robertson *et al.*, 2002; Chauhan *et al.*, 2010). However, the estimated rate in leaf initiation of tomato was slightly higher than that reported in literature (Table 1). Estimated RUE of maize and tomato are within the range reported in literature (Table 1). However, the estimated RUE of mungbean is greater than previously reported values. The predicted yields of the three crops were in agreement with the observed data. The variability of yield prediction was in the range of 13.7% for maize, 27.9% for mungbean, and 21.6% tomato. These observations are comparable with the evaluation of maize in Asia using APSIM (Gaydon *et al.*, 2017).

Contributions to modelling of leaf growth

Leaf growth in this work is modelled using leaf expansion duration, leaf expansion rate, and biomass partitioning to leaves, all of which are driven by CTT. The gradual increase in leaf expansion duration observed in maize in this study from 1st to 13th leaf, and the subsequent decrease towards flag leaf is in agreement with patterns reported previously (Zur *et al.*, 1989; Reid *et al.*, 1990). In contrast, the rate leaf expansion increased from first to 20th leaf and then decreased to flag leaf. The Incorporation of such details contributed to the improved predictive accuracy of the models in this study. Inadequate attention had been given to modelling rates of leaf expansion in mungbean and tomato in the past. Therefore, the present study fills this information gap on the CTT-dependent leaf area expansion duration and expansion rate of these two crops. Furthermore, simulation of leaf senescence behaviour in all three crops using genetic parameters derived under

Table 1: Estimated and literature reported values of development and growth-related variables in maize, mungbean and tomato

Variable	Crop	Measured values in this study	Values reported in the literature	Source
Thermal time for flowering (°C days)	Maize	984±43	1000	Plenet <i>et al.</i> , 2000; Kim <i>et al.</i> , 2012 Chauhan and Rachaputi, 2014; Singh and Singh, 2011 Bouzo and Favaro, 2014; Palaretti <i>et al.</i> , 2012; Pathak and Stoddard, 2018
	Mungbean	652±19	630	
	Tomato	660±17	689	
Thermal time for maturity (°C days)	Maize	1835±38	1800	Plenet <i>et al.</i> , 2000; Kim <i>et al.</i> , 2012 Chauhan and Rachaputi, 2014; Singh and Singh, 2011 Bouzo and Favaro, 2014; Palaretti <i>et al.</i> , 2012; Pathak and Stoddard, 2018
	Mungbean	1140±11	1250	
	Tomato	2019±53	1548	
Leaf appearance rate (°C days leaf ⁻¹)	Maize	43.4	47.6-65.5	Birch <i>et al.</i> , 1998; Padilla and Otegui, 2005 Robertson <i>et al.</i> , 2002; Chauhan <i>et al.</i> , 2010 Jones <i>et al.</i> , 1991 Boote <i>et al.</i> , 2012
	Mungbean	96.5	100.0	
	Tomato	66.6	34.5-60.0	
RUE (g MJ ⁻¹)	Maize	2.48	2.27-3.8	Andrade <i>et al.</i> , 1993; Lindquist <i>et al.</i> , 2005 Muchow <i>et al.</i> , 1993; Chauhan <i>et al.</i> , 2010; Laekemariam and Worku, 2013 Scholberg <i>et al.</i> , 2000; Adamowicz and Bot, 2008
	Mungbean	1.52	0.94-1.74	
	Tomato	0.72	0.51-1.05	

subsistence farming environments for locally-adapted varieties contributed to the improved predictive capability of the present models.

CONCLUSIONS

We conclude that in-country development of simpler crop models is a viable alternative to expending a similar effort to parameterize a globally available full-system crop model. We also argue that in addition to having simpler models that simulate the performance of local germplasm grown in local farming conditions, this pathway has the added benefits of: (a) developing modelling expertise among local researchers; and (b) possibility of developing simpler sub-models that simulate crop performance under key abiotic and biotic stresses.

Supplementary Information

The supplementary material available at [xxxxxxx](#)

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