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Plant growth modeling in six landraces of Bambara groundnut seed production (*Vigna subterranea*)

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Abstract. *Rosyad A, Ilyas S, Qadir A, Suhartanto MR, Sopandie D. 2025. Plant growth modeling in six landraces of Bambara groundnut seed production* (Vigna subterranea). *Biodiversitas 26: 2097-2105.* The unavailability of high-quality seeds, low productivity, and lack of information on ecophysiological responses are the major problems in Bambara groundnut (*Vigna subterranea*) seed production. In this context, agro-climate components influencing plant growth include solar radiation and temperature. These components are quantified in the form of a plant model to influence growth through metabolic processes. A dynamic model is used as a solution to the problem. Therefore, this research aimed to create a dynamic model for the seed production of six Bambara groundnut landraces and to study the physiological processes related to yield. The stages in the model construction included (i) identifying system components, (ii) model construction, (iii) simulation, and (iv) validation. The ecophysiological reaction of plants to temperature and solar radiation in photosynthesis and respiration was constructed using the growth model. Model construction used the STELLA software. Each landrace has different input components at each stage of development, including the carbohydrate partition coefficient, specific leaf area, extinction coefficient, and light usage efficiency. Simulated seed productivity on Tasikmalaya, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik landrace was 2,115 kg ha^{-1}, 2,263 kg ha^{-1}, 1,975 kg ha^{-1}, 1,890 kg ha^{-1}, 2,179 kg ha^{-1}, and 1,975 kg ha^{-1}, respectively. The level of validity of the Tasikmalaya landrace, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik growth model reached 82.4%, 82.4%, 94.1%, 82.4%, 88.2%, and 82.4%, respectively. These models are considered fit as the validity is greater than 80%. The seed production growth model with pod dry weight output was named 'The BAMSeed Model'. In practice, this model could benefit the researchers in predicting the yield of bambara groundnut using the selected system components.

Keywords: BAMSeed Model, model construction, pod dry weight, prediction, simulation

Abbreviations: LAI: Leaf Area Index; SLA: Specific Leaf Area; MCL: Model Construction Layer

INTRODUCTION

Bambara groundnut (*Vigna subterranea* (L) Verdc) is one of Africa's most important legume crops. This crop is recognized as a useful and nutrient-dense food source during famine and the ability to grow in unfavorable environment (Mayes et al. 2019; Mbosso et al. 2020; Paliwal et al. 2020; Khan et al. 2021). In Indonesia, Bambara groundnut has long been cultivated, especially in the provinces of West Java, East Java, Lampung, West Nusa Tenggara, and East Nusa Tenggara, and several landraces are available with some extent of genetic variability (Al Hamdi et al. 2020). Furthermore, Bambara groundnut has a carbohydrate content of 64.4%, 23.6% protein, 6.5% fat, and 5.5% fiber (Tan et al. 2020), as well as potassium, magnesium, calcium, iron, and phosphorus (Maphosa et al. 2022). Mubaiwa et al. (2018) stated that Bambara groundnuts were comparatively underused and small-scale farming compared to other important commercial crops. Bambara groundnuts have the potential to diversify agri-food systems and improve dietary and planetary sustainability by concentrating on areas that span the value chain from genetics, agroecology, nutrition, processing, and socioeconomic potential (Tan et al. 2020).

In African countries, the average productivity of Bambara groundnut ranged from 0.5-3 tons ha^{-1} between 1999 to 2018 (Bonny et al. 2019; Majola et al. 2021). In tropical regions, the yield was recorded as 0.38 to 2.00 tons ha^{-1} (Al Hamdi et al. 2020; Khan et al. 2021). According to Mayes et al. (2019) there is a discrepancy between the potential yields of 3 tons ha^{-1} attained through production optimization and the typical yields of 0.85 tons ha^{-1}. The low yields are due to a lack of funding for managerial, agronomic, and genetic research (Majola et al. 2021). There were still a few studies of the Bambara growth model, while the studies for other commodities were numerous. The CROPGRO model has been adapted for more than 20 species so far (Karunaratne et al. 2024), including carinata as a bioenergy crop (Boote et al. 2021) and guar (Boote et al. 2023).

Landraces with improved genetic variability form the majority of Bambara groundnut. This is shown by the significant differences in nutritional (Halimi et al. 2019) and morphological (Unigwe et al. 2016) characteristics. Farmers can benefit from genetic variability because certain landrace population members may offer yield stability, stress tolerance, and local adaptation (Dwivedi et al. 2016). The production of high-quality seeds requires a thorough understanding of the developmental phase during which seeds accumulate and store energy before initiating growth. The influence of induced factors, such as agro-climatic conditions, primarily determines the success of seed development.

Agro-climate components influencing plant growth include solar radiation and temperature, which interact with the system components through metabolic processes, such as photosynthesis and respiration. The products of photosynthesis are allocated and used in various plant parts for organ maintenance and stored as food reserves (Hartmann et al. 2020). According to Guo et al. (2021), there is positive correlation between solar radiation intensity and root dry weight, shoot dry weight, and root/shoot ratio. The components in the system can be quantified in the form of a plant growth model.

The growth process has been widely analyzed through the behavior of plants and made into a model to produce an estimation function. However, this model is more of a mathematical summary of the available data and does not include changes in time (Qadir 2012). The growth model accurately describes changes in circumstances over time (Ahmed et al. 2020). The study of Bambara growth model by Karunaratne et al. (2024) used leaf area index, light extinction as a system component, while the present study added carbohydrate partition as a different component. In the present study, several landraces of Bambara groundnut were used to understand the validity of the model for each landrace and to provide an idea of the broadness of application of the developed models. Therefore, the purpose of this research was to create a plant growth model for the seed production of six Bambara groundnut landraces and to study the physiological processes related to yield. The developed models could be used to determine agro-climate conditions suitable for enhancing seed production.

MATERIALS AND METHODS

Research area

The research covered two activities: desk research and an experiment. The desk research was carried out at the Department of Agronomy and Horticulture, Institut Pertanian Bogor, Bogor, Indonesia. The experiment was carried out in the Sawah Baru experimental field (6° 33'51 "S 106° 44'05 " E) and the Seed Storage and Quality Testing Laboratory, Department of Agronomy and Horticulture, Institut Pertanian Bogor, between July 2022 and August 2023.

Plant materials

The Bambara groundnut seeds consisted of Tasikmalaya, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik landraces, which local farmers commonly used. Apart from the regions, landraces had different seed sizes. Seeds were obtained from producers in the areas according to the landrace origin, harvested in December 2021 (Gresik landrace), January 2022 (Tasikmalaya landrace), March 2022 (Sumedang and Small Sumedang landraces), and April 2022 (Sukabumi and Bogor landraces). Before planting, the seeds were stored in a controlled storage room (temperature of ±16°C, relative humidity ±65%) at the Department of Agronomy and Horticulture, Institut Pertanian Bogor.

Procedures

The research was conducted in phases using the following procedures, which were based on Qadir's (2012) modified modeling method.

Identification of system components

Identification is carried out on a group of processes playing a significant role in the plant growth system. The primary process is selected based on the excellent growth process of changing and maintaining the plant organ structure. Identification of system components is also carried out on processes or groups playing a role in changes. The components of the growth process are identified in terms of processes supporting the system and agro-climatic factors. Components of the development process are identified regarding the influence of agro-climatic factors influencing the development phase.

Construction model

The first step in building a model is creating a flow diagram. Furthermore, logical-mathematical links between system variables and system chaining are determined using Stella software version 9.0.2. The flow diagram is created in a Forester by identifying the components of the plant growth system. Quantitative relationships in the form of mathematical equations, logic, and model components are also determined through literature research and experiments.

A total of four replications of a Randomized Complete Block Design (RCBD) were used in this one-factor seed production experiment. The landraces factor consisted of six levels, namely Tasikmalaya, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik landraces. The rainfall during the experiment was an average of 230,62 mm month^{-1}. The average temperature was 25.7°C with a relative humidity of 75.2%. Additionally, the experiment started with tilling the soil 14 days before planting, and the samples were taken for soil analysis. Chicken manure and husk (2:1) were given at a dose of 2 tons ha^{-1}. Dolomite lime ($CaMg(CO_3)_2$) was added before planting at a dose of 500 kg ha^{-1} (pH 5.3). A seed was placed in each of the 24 plots, measuring 13 m by 13 m and spaced 60 cm by 25 cm apart. Subsequently, inorganic fertilizer was administered at a dose of 50 kg ha^{-1} of Urea, 100 kg ha^{-1} of SP-36, and 75 kg ha^{-1} of KCl (Sari et al. 2021). The Dramaga Climatology Station provided the temperature and sun radiation agro-climate components. Plant components in the form of maintenance respiration coefficient (km) are used as results by Kropff and Van Laar (1993) (km roots = 0.005; petioles = 0.035; leaves = 0.015; pods = 0.15). This research also recorded the stage of plant growth in the field, the input components of light consumption efficiency, extinction coefficient, Specific Leaf Area (SLA), and participant coefficient. During growth, photosynthesis products were computed using the equation:

$$Pn = \varepsilon * (1 - \exp^{(-k\ LAI)}) * Qs$$

Where:
Pn : Photosynthesis products (Pn)
LAI : Leaf Area Index
ε : Light use efficiency
k : Extinction coefficient
Qs : The solar radiation that reaches the plant canopy

The light use efficiency can be calculated based on the ratio of plant dry weight to the amount of radiant energy intercepted by the canopy over a given period. The light extinction coefficient is calculated based on the results of radiation measurements above the canopy, below the canopy, and leaf area at each phase of plant development. The carbohydrate partition coefficient was calculated at each developmental phase by dividing the organ's dry weight by the total dry weight.

The Leaf Area (LA) and Specific Leaf Area (SLA) were measured using grid and drying methods, respectively. The SLA was calculated using the following equation (Freschet et al. 2015):

$$SLA = \frac{LA}{W}$$

Where: W is the leaf dry mass.

The pod dry weight was used to validate the model. Input observations and component validation were carried out by destructively taking three plants per replication weekly from 14-112 Days After Planting (DAP). Seed quality components observed included moisture content (%), vigor index (%), and germination capacity (%).

Simulation

The simulation was carried out by entering temperature and sun radiation as inputs using the Stella Construction Layer Model and the Stella Layer Interface Version 9.0.2. The results are presented in graphical form, and the logic level was assessed based on the criteria that the growth pattern followed a sigmoid or exponential pattern in the plant development phase.

Validation

Model validation is conducted to assess the atmospheric simulation model against actual results through qualitative methods. Qualitative validation tests use graphs visualizing the model output in the form of the pod dry weight based on specific times or periods. The model is valid when the simulation results fall within the actual standard deviation interval (Lowe et al. 2018).

Data analysis

A Duncan's Multiple Range Test (DMRT) was performed at the α = 5% threshold of significance after data were evaluated using analysis of variance. DMRT is used to identify specific group differences after finding a significant ANOVA result, with a focus on balancing statistical power and error rates in multiple comparisons.

RESULTS AND DISCUSSION

Identification of system components

The respiration rate and the distribution of photosynthetic products across plant organs determine the level of growth. Photosynthesis products are distributed from the leaves through the phloem, with the role of sugar transporters. The ability of plants to bind solar energy in the process and the interaction with environmental factors can be reflected in the accumulation of dry weight, which is distributed to roots, internodes, petioles, leaves, and pods. The plant development phase greatly influences the partition of carbohydrates to plant organs in the growth system. The plant development phase is determined based on the planting time to the field emergence phase, the field emergence phase to the maximum vegetative phase, the maximum vegetative phase to the 50% flowering phase, and the 50% flowering phase to the mature pods phase. The system components were identified by focusing on the key biological structures and molecular components involved in photosynthesis and respiration-related processes. These components are central to how cells capture, store, and utilize energy in both processes.

Construction model

Growth system flow diagram

The plant-growth system flow diagram is arranged based on external and plant factors in the form of photosynthesis and respiration processes. Agro-climate, as an external factor, influences the model through solar radiation and temperature. In this context, solar radiation affects the growth model through energy flow. The diagram describes photosynthetic flow to plant organs (roots, petioles, leaves, and pods) and the loss through respiration (Figure 1).

Quantitative relationships of growth models

The growth model is based on the relationship between the production of photosynthesis products (Pn) and the amount of radiation intercepted by plants. Pn for each landrace varies in the value of the Leaf Area Index (LAI), light use efficiency (ε), and extinction coefficient (k) concerning the structure of the plant canopy, and Qs is the solar radiation reaching the plant canopy. Variations in coefficient values at each landrace show differences in photosynthesis products produced.

The ANOVA result showed both landrace and replication in each development phase are significantly different (P<001) on almost all variables (Table 1). Genetic variability in Bambara groundnut landraces is relatively high. Studies have shown that these landraces exhibit significant genetic diversity, which is essential for crop improvement and adaptation to changing environments (Al Hamdi et al. 2020; Sari et al. 2021).

Light use efficiency (ε) describes the use of light for growth (Legendre and van Iersel 2021). The efficiency value shows the ability to convert the energy received into plant dry weight. The ε values for six Bambara groundnut landraces at the initial growth stage until mature pods are presented in Table 2.

The ε value shows significantly different results at each stage and growth phase. Table 2 shows that the value is high at the stage from flowering to maturity. Tasikmalaya landrace had the highest ε values in the planting to field emergence and field emergence to vegetative phases. The Sukabumi, Sumedang, Bogor, and Gresik landraces showed results that were not significantly different in the vegetative to 50% flowering phases. Meanwhile, Sumedang and Gresik landraces reported results that were not significantly different at the 50% flowering to mature pod phases. The amount of incoming radiation that reaches the plant surface, the LAI, the position or angle of the leaves, and the distribution within the canopy affect the efficient use of light by plants.

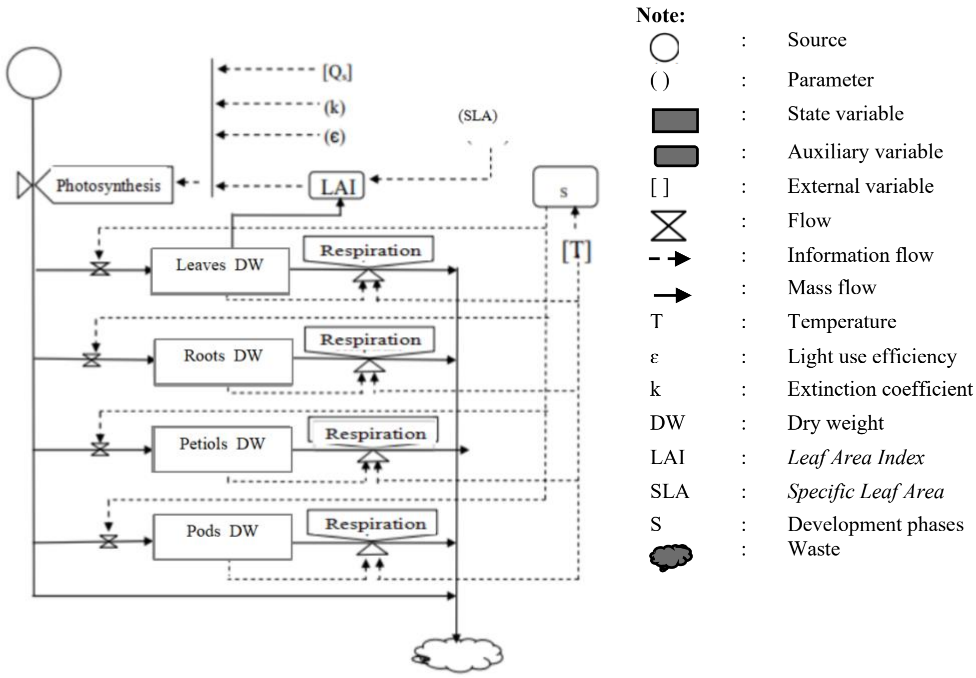

Figure 1. The forester diagram of the plant growth model of Bambara groundnut

Table 1. Mean squares of light use efficiency, light extinction coefficient, specific leaf area, carbohydrate partition coefficient of bambara groundnut landraces

Variance components	Mean squares						
	LUE	LEC	SLA	CPC(r)	CPC(pt)	CPC(l)	CPC(pd)
Landraces							
Planting-field emergence	3.3×10^{-8}**	-	7.1×10^{-4}**	2.1×10^{-3}**	5.6×10^{-4}**	1.6×10^{-3}**	-
Field emergence-vegetative	7.4×10^{-7}**	8.2×10^{-5}**	1.5×10^{-3}**	5.6×10^{-4}**	4.4×10^{-4}**	4.1×10^{-4}**	-
Vegetative-50% flowering	8.9×10^{-5}**	2.0×10^{-3}**	2.8×10^{-3}**	2.1×10^{-4}**	1.1×10^{-3}**	9.1×10^{-3}**	3.4×10^{-3}**
50% flowering-mature pods	1.9×10^{-4}**	4.2×10^{-5}**	8.0×10^{-4}**	1.00×10^{-9}	1.3×10^{-3}**	1.9×10^{-3}**	5.4×10^{-3}**
Replications							
Planting-field emergence	5.6×10^{-7}**	-	2.2×10^{-2}**	1.7×10^{-2}**	1.3×10^{-1}**	5.4×10^{-1}**	-
Field emergence-vegetative	4.5×10^{-6}**	2.9×10^{-3}**	0.5×10^{-2}**	1.0×10^{-2}**	1.7×10^{-1}**	5.1×10^{-1}**	-
Vegetative-50% flowering	4.7×10^{-4}**	5.3×10^{-3}**	3.5×10^{-2}**	1.8×10^{-3}**	2.5×10^{-1}**	4.4×10^{-1}**	2.7×10^{-3}**
50% flowering-mature pods	1.6×10^{-4}**	8.1×10^{-5}**	3.6×10^{-2}**	6.0×10^{-4}**	1.6×10^{-1}**	1.8×10^{-1}**	1.6×10^{-1}**

Note: LUE: Light Use Efficiency; LEC: Light Extinction Coefficient; SLAI: Specific Leaf Area; CPC: Carbohydrate Partition Coefficient; r: Roots; pt: Petioles; l: Leaves; pd: Pods; **: significantly different at P<0.01

Table 2. Light use efficiency (ε) in four developmental phases of six Bambara groundnut landraces (kg MJ^{-1})

Development phase	Tasikmalaya	Sukabumi	Sumedang	Small Sumedang	Bogor	Gresik
Planting-field emergence	7.8×10^{-4}a	6.3×10^{-4}b	6.4×10^{-4}b	4.7×10^{-4}c	5.6×10^{-4}bc	5.7×10^{-4}b
Field emergence-vegetative	2.5×10^{-3}a	1.7×10^{-3}b	1.9×10^{-3}b	1.0×10^{-3}c	1.6×10^{-3}b	1.6×10^{-3}b
Vegetative-50% flowering	1.3×10^{-2}b	2.2×10^{-2}a	1.8×10^{-2}a	9.7×10^{-3}b	2.2×10^{-2}a	2.1×10^{-2}a
50% flowering-mature pods	5.9×10^{-3}b	4.4×10^{-3}b	8.0×10^{-3}b	1.8×10^{-2}a	3.7×10^{-3}b	2.3×10^{-2}a

Note: In the DMRT test, numbers followed by the same letter in the same row show an insignificant difference at the 5% significance level

The capacity to absorb solar radiation is correlated with the light extinction coefficient (k). The landraces of Small Sumedang, Bogor, and Gresik showed k values that were not significantly different in the field-emergence phase. Gresik landrace has the highest k value in the vegetative to 50% flowering phases. The Landraces of Tasikmalaya, Sumedang, and Small Sumedang showed k values that were not significantly different at the 50% flowering and mature pod phases (Table 3).

In the growth model, LAI is an auxiliary and internal variable because it cannot be computed directly; this quantity is expressed as a function of leaf area and dry weight at each plant phase, or SLA. Table 4 shows the results of SLA measurements as a growth model constant.

Landraces of Tasikmalaya, Sukabumi, and Bogor showed SLA values similar in the planting to the field emergence phase. Tasikmalaya and Bogor Landraces had SLA values that were not significantly different in the field emergence to the vegetative phase. Similarly, Bogor, Sukabumi, and Gresik landraces showed SLA values that were not significantly different in the 50% vegetative to flowering phases. Gresik, Bogor, and Small Sumedang landraces had significantly different SLA values at the 50% flowering and mature pod phases. The area of the leaf that absorbed light and CO_2 on the biomass, influencing interception and use efficiency, was described by the SLA value (Beechey-Gradwell et al. 2020).

The amount of flow of photosynthesis products in the form of carbohydrate compounds was determined by the magnitude of the carbohydrate partition coefficient (Farhat et al. 2016). In this context, each organ uses the allocated carbohydrate for growth and maintenance. Table 5 presents the results from measuring the carbohydrate partition coefficient as a growth model constant.

Table 3. Light extinction coefficients (k) at various developmental phases of six Bambara groundnut landraces

Development phase	Tasikmalaya	Sukabumi	Sumedang	Small Sumedang	Bogor	Gresik
Planting-field emergence	0.000a	0.000a	0.000a	0.000a	0.000a	0.000a
Field emergence-vegetative	0.035d	0.043bc	0.042c	0.048a	0.049a	0.047a
Vegetative-50% flowering	0.055b	0.068ab	0.077ab	0.012c	0.059b	0.085a
50% flowering-mature pods	0.011a	0.004cd	0.011a	0.009ab	0.007bc	0.002d

Note: Numbers followed by the same letter in the same row indicate that they are not significantly different in the DMRT test with a significance level of 5%

Table 4. SLA measurement results as a constant for the growth model of six Bambara groundnut lines (kg ha^{-1})

Development phase	Tasikmalaya	Sukabumi	Sumedang	Small Sumedang	Bogor	Gresik
Planting-field emergence	0.1363a	0.1383a	0.102c	0.1048c	0.1267ab	0.1197b
Field emergence-vegetative	0.2118a	0.1859b	0.156c	0.1574c	0.2008ab	0.1826b
Vegetative-50% flowering	0.1475bc	0.1686ab	0.128cd	0.1115d	0.1936a	0.1727ab
50% flowering-mature pods	0.1322d	0.1507bc	0.1424cd	0.1634ab	0.1637ab	0.1772a

Note: In the DMRT test, numbers followed by the same letter in the same row indicate an inconsequential change at a 5% significance level

Table 5. Carbohydrate partition coefficient (p) in four developmental phases of six Bambara groundnut landraces

Development phase	Tasikmalaya	Sukabumi	Sumedang	Small Sumedang	Bogor	Gresik
Roots						
Planting-field emergence	0.120ab	0.100b	0.060c	0.140a	0.110b	0.110b
Field emergence-vegetative	0.100a	0.070b	0.070b	0.100a	0.080b	0.080b
Vegetative-50% flowering	0.040a	0.040a	0.040a	0.040a	0.020c	0.030b
50% flowering-mature pods	0.020a	0.020a	0.020a	0.020a	0.020a	0.020a
Petioles						
Planting-field emergence	0.290b	0.310a	0.310a	0.280b	0.290b	0.280b
Field emergence-vegetative	0.350a	0.350a	0.340ab	0.320c	0.330bc	0.330bc
Vegetative-50% flowering	0.410b	0.420ab	0.420ab	0.430a	0.390c	0.380c
50% flowering-mature pods	0.330b	0.310cd	0.350a	0.350a	0.300d	0.320bc
Leaves						
Planting-field emergence	0.590bc	0.580c	0.640a	0.580c	0.590bc	0.610b
Field emergence-vegetative	0.560b	0.580a	0.590a	0.580a	0.590a	0.590a
Vegetative-50% flowering	0.540b	0.650a	0.520b	0.530b	0.520b	0.490b
50% flowering-mature pods	0.350b	0.330bc	0.340bc	0.390a	0.330bc	0.320c
Pods						
Vegetative-50% flowering	0.015c	0.097a	0.044bc	0.019c	0.067ab	0.014c
50% flowering-mature pods	0.300c	0.365a	0.321bc	0.252d	0.359ab	0.342ab

Note: In the DMRT test, numbers that are followed by the same letter in the same row show a substantial difference at the 5% significance level

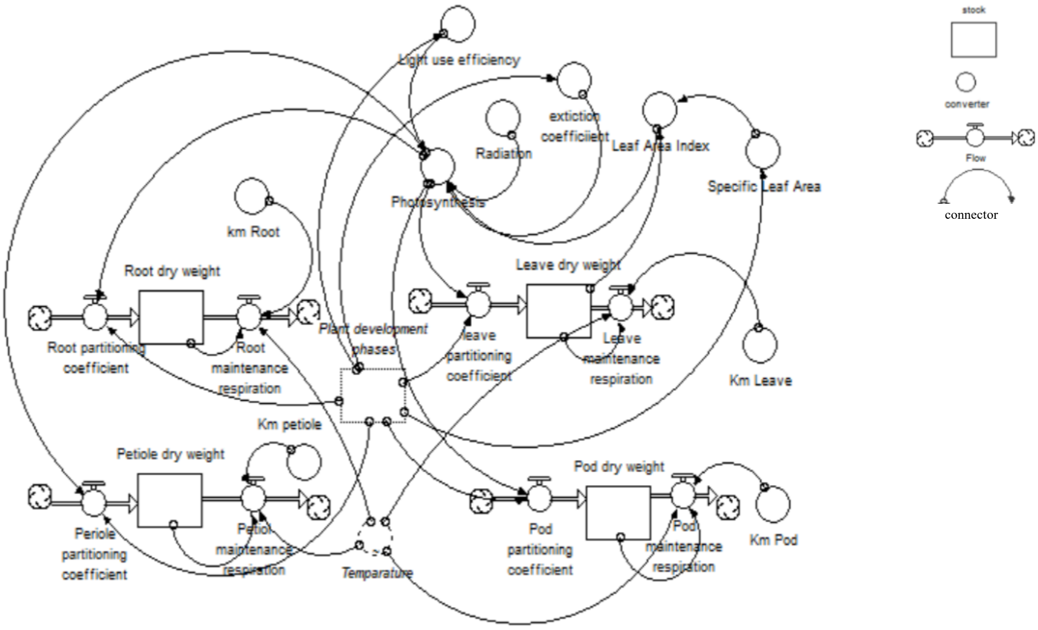

Figure 2. Model Construction Layer (MCL) of Bambara groundnut growth

Organ carbohydrate partition coefficients vary for each landrace at each phase of development. The partition coefficient of each plant for roots ranged from 2-12%, petioles 29-43%, leaves 32-65%, and pods 25-37%. The carbohydrates allotted to each organ are used for growth and upkeep through breathing. The dry weight of plant organs is the accumulation of the mass flow of carbohydrate compounds from photosynthesis products after deducting energy through maintenance respiration (Rm). Temperature is an essential factor influencing the maintenance respiration rate (km), which increases two times for every 10°C. Therefore, the effect of temperature on the maintenance respiration rate can be calculated based on the equation (Gholipouri et al. 2010):

$$Rm = \frac{km.2^{(T-20)}}{10 \times \text{Dry Weight}}$$

Construction of system components using Stella software version 9.0.2

The Model Construction Layer (MCL) in Stella software is used to construct a growth model (Figure 2). MCL is arranged based on flow diagrams and quantitative relationships in photosynthesis, carbohydrate partitioning, and respiration processes.

Stocks are described due to the accumulation of mass flow since dry weight is used. The flows are described as the functions to increase or decrease stocks. In this process, photosynthesis is translocated to stocks through flow. Converters store constants and input equations, perform calculations from other inputs, as well as save data in graphics. Meanwhile, connectors are used to connect elements of a model.

Simulation

Temperature and solar radiation are used as input variables in the simulation model. Figure 3 shows the daily mean temperature and solar radiation during the crop cycle. The temperature measured was a maximum and minimum of 27.6°C and 23.8°C, respectively. Meanwhile, solar radiation measured was a maximum and minimum of 782 cal m^{-2} and 79 cal m^{-2}, respectively. The simulation results of the growth model for six Bambara groundnut landraces for the pod dry weight variable from the planting until the mature pod phase are presented in Figure 4. Pod filling starts after the plants are 56 DAP, marked by the accumulation of dry weight and reaching physiological maturity. The physiological maturity of the Tasikmalaya, Sumedang, and Small Sumedang landraces occurs at 108 DAP, while the Sukabumi, Bogor, and Gresik landraces occur at 110 DAP. Furthermore, the dry weight of pods at physiological maturity for Tasikmalaya landraces, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik is 1,959 kg ha^{-1}, 2,096 kg ha^{-1}, 1,829 kg ha^{-1}, 1,751 kg ha^{-1}, 2,018 kg ha^{-1}, and 1,829 kg ha^{-1}, respectively. Under the condition of seed moisture content of 12%, the production in each landrace is 2,115 kg ha^{-1}, 2,263 kg ha^{-1}, 1,975 kg ha^{-1}, 1,890 kg ha^{-1}, 2,179 kg ha^{-1}, and 1,975 kg ha^{-1}. The variety of model input component values affects the variation in dry weight among landraces.

Validation

The model was validated by contrasting the appropriateness of variable values from real field observations with the outcomes. The validation results of dry weight for each landrace are presented in Figure 5. The model was declared valid because the simulated dry weight pattern was within the standard deviation interval of the actual observation. The level of validity of the Tasikmalaya landraces, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik growth model reached 82.4%, 82.4%, 94.1%, 82.4%, 88.2%, and 82.4%, respectively. The growth model with dry weight output is named 'The BAMSeed Model'.

The validation of the model was relatively higher than the others for Bambara groundnut. In this context, Cornellinsen (2005) showed the actual and estimated BamGro model of pod weights on three Bambara groundnut landraces (Uniswa Red, OM1, AS17). There was a very strong correlation between actual and estimated pod yield in AS17 (r = 0.95), Uniswa Red (r = 0.61), and OM1 (r = 0.63). However, the shape of the fitted curve was similar to the actual values because the BamGro model estimated the pod filling.

Seed quality status under actual pod dry weight conditions varied for each race. The results are presented in Table 6, and water content ranges from 11.05 to 12.52%. The Bogor and Gresik Landraces on the vigor index variable showed the highest results compared to others at 76.00% and 72.00%. Seed viability using germination power as a benchmark showed results that were not significantly different for the Sukabumi, Bogor, Tasikmalaya, and Gresik landraces, with germination values ranging from 94.00 to 85.25%.

Table 6. Seed quality of six Bambara groundnut landraces

Variable	Tasikmalaya	Sukabumi	Sumedang	Small Sumedang	Bogor	Gresik
Moisture content (%)	12.52a	12.21a	12.46a	11.60ab	11.05b	12.16a
Vigour index (%)	50.00c	51.25c	58.75bc	62.00b	76.00a	72.00a
Germination rate (%)	89.25ab	94.00a	88.00bc	82.75c	94.00a	85.25ab

Note: Numbers followed by the same letter in the same row show insignificant differences in the DMRT test at a level of 5%

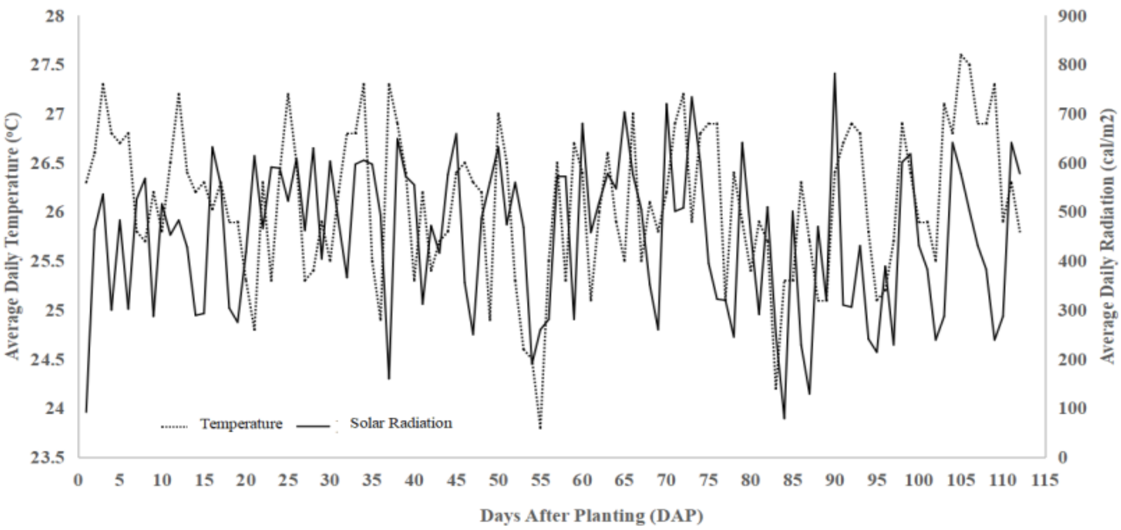

Figure 3. Data of temperature and solar radiation during planting of Bambara groundnut in the field

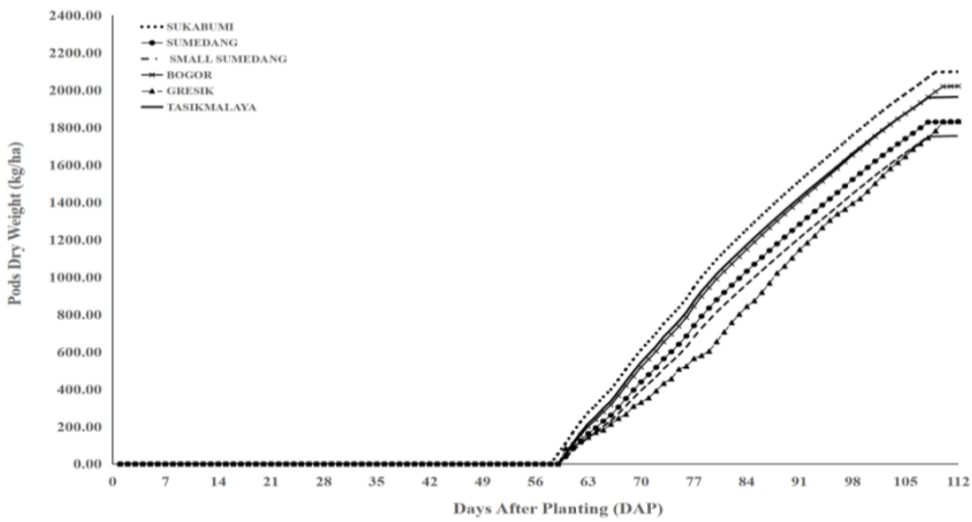

Figure 4. Simulation results of the dry weight of six landraces Bambara groundnut pods

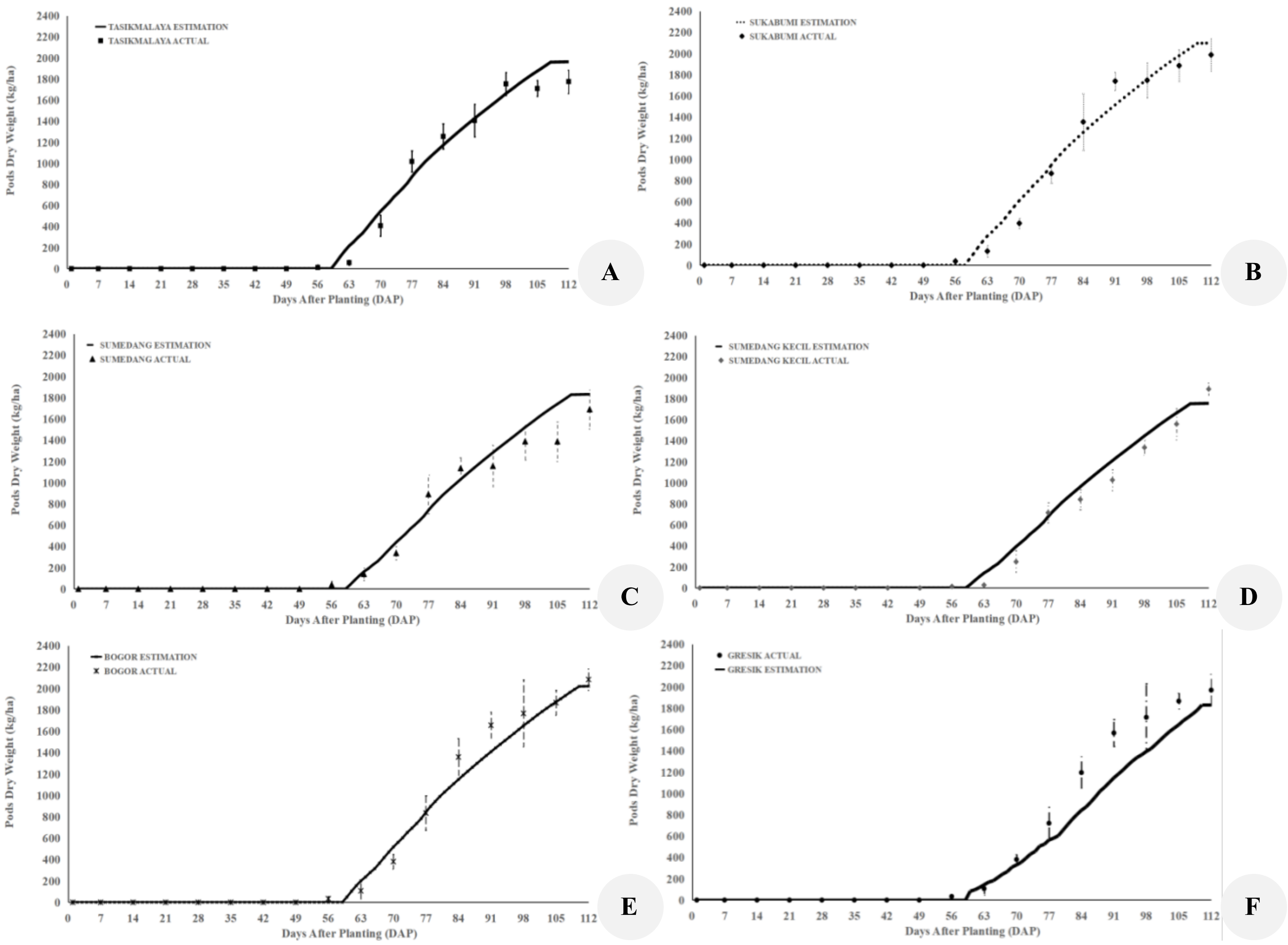

Figure 5. Validation of pod dry weight in landraces of: A. Tasikmalaya; B. Sukabumi; C. Sumedang; D. Small Sumedang; E. Bogor; F. Gresik

In conclusion, a seed production growth model with simulated dry weight output of six landraces of Bambara groundnut pods could be constructed validly. Light usage efficiency, extinction coefficient, SLA, and carbohydrate partition coefficient were the model input components that changed for every plant at the stage of development. Seed productivity from simulation results in the Tasikmalaya, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik land areas was 2,115 kg ha^{-1}, 2,263 kg ha^{-1}, 1,975 kg ha^{-1}, 1,890 kg ha^{-1}, 2,179 kg ha^{-1}, and 1,975 kg ha^{-1}, respectively. The level of validity of the Tasikmalaya, Sukabumi, Sumedang, Small Sumedang, Bogor, and Gresik growth model reached 82.4%, 82.4%, 94.1%, 82.4%, 88.2%, and 82.4%, respectively. In the future, research models using other physiological traits with other types of landraces were suggested. The seed production growth model with the simulated output of pod dry weight is named 'The BAMSeed Model'. In practice, this model could benefit the researchers in predicting the yield of bambara groundnut using the selected system components.

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REFERENCES

Ahmed M, Raza MA, Hussain T. 2020. Dynamic modeling. In: Ahmed M (eds). Systems Modeling. Springer, Singapore. DOI: 10.1007/978-981-15-4728-7_4.

Al Hamdi MFF, Setiawan A, Ilyas S, Ho WK. 2020. Genetic variability of Indonesian landraces of *Vigna subterranea*: Morphological characteristics and molecular analysis using SSR markers. Biodiversitas 21 (9): 3929-3937. DOI: 10.13057/biodiv/d210902.

Beechey-Gradwell Z, Cooney L, Winichayakul S, Andrews M, Hea SY, Crowther T, Roberts N. 2020. Storing carbon in leaf lipid sinks enhances perennial ryegrass carbon capture especially under high N and elevated CO_2. J Exp Bot 71: 2351-2361. DOI: 10.1093/jxb/erz494.

Bonny BS, Adjoumani K, Seka D, Koffi KG, Kouonon LC, Koffi KK, Bi IAZ. 2019. Agromorphological divergence among four agro-ecological populations of Bambara groundnut (*Vigna subterranea* (L.)

Verdc.) in Côte d'Ivoire. Ann Agric Sci 64 (1): 103-111. DOI: 10.1016/j.aoas.2019.04.001.

Boote KJ, Hoogenboom G, Ale S, Adams C, Shrestha R, Mvuyekure RF, Himanshu SK, Grover K, Angadi S. 2023. Adapting the CROPGRO model to simulate growth and yield of guar, *Cyamopsis tetragonoloba* L, an industrial legume crop. Ind Crops Prod 197: 116596. DOI: 10.1016/j.indcrop.2023.116596.

Boote KJ, Seepaul R, Mulvaney MJ, Hagan AK, Bashyal M, George S, Small I, Wright DL. 2021. Adapting the CROPGRO model to simulate growth and production of *Brassica carinata*, a bio-fuel crop. GCB Bioenergy 13 (7): 1134-1148. DOI: 10.1111/gcbb.12838.

Cornelissen RLEJ. 2005. Modelling variation in the physiology of Bambara Groundnut (*Vigna subterranea* (L.) Verdc.) [Dissertation]. Cranfield University, Silsoe.

Dwivedi SL, Ceccarelli S, Blair MW, Upadhyaya HD, Are AK, Ortiz R. 2016. Landrace germplasm for improving yield and abiotic stress adaptation. Trends Plant Sci 21 (1): 31-42. DOI: 10.1016/j.tplants.2015.10.012.

Farhat N, Elkhouni A, Zorrig W, Smaoui A, Abdelly C, Rabhi M. 2016. Effects of magnesium deficiency on photosynthesis and carbohydrate partitioning. Acta Physiol Plant 38: 145. DOI: 10.1007/S11738-016-2165-z.

Freschet G, Swart EM, Cornelissen JHC. 2015. Integrated plant phenotypic responses to contrasting above-and below-ground resources: Key roles of specific leaf area and root mass fraction. New Phytol 206 (4): 1247-1260. DOI: 10.1111/nph.13352.

Gholipouri A, Sedghi M, Sharifi RS, Heydari A. 2010. Simulating photosynthesis, respiration and dry matter production in annual crops. J Phytol 2 (1): 1-6.

Guo X, Yang Y, Liu H et al. 2021. Effects of solar radiation on root and shoot growth of maize and the quantitative relationship between them. Crop Sci 61 (2): 1414-1425. DOI: 10.1002/CSC2.20416.

Halimi RA, Barkla BJ, Mayes S, King GJ. 2019. The potential of the underutilized pulse bambara groundnut (*Vigna subterranea* (L.) Verdc.) for nutritional food security. J Food Compos Anal 77: 47-59. DOI: 10.1016/j.jfca.2018.12.008.

Hartmann H, Bahn M, Carbone M, Richardson AD. 2020. Plant carbon allocation in a changing world-challenges and progress. New Phytol 227 (4): 981-988. DOI: 10.1111/nph.16757.

Karunaratne AS, Hoogenboom G, Boote KJ. 2024. Adapting the CROPGRO model to simulate growth, development, and yield of Bambara groundnut (*Vigna subterranea* L. Verdc), an underutilized crop. Eur J Agron 159:127279. DOI: 10.1016/j.eja.2024.127279.

Khan MMH, Rafii MY, Ramlee SI, Jusoh M, Al-Mamun M. 2021. Bambara groundnut (*Vigna subterranea* L. Verdc): A crop for the new millennium, its genetic diversity, and improvements to mitigate future food and nutritional challenges. Sustainability 13 (10): 5530. DOI: 10.3390/su13105530.

Kropff M, Van Laar HH. 1993. Modelling Crop-Weed Interactions. CABI, Wallingford.

Legendre R, van Iersel MW. 2021. Supplemental far-red light stimulates lettuce growth: Disentangling morphological and physiological effects. Plants 10 (1): 166. DOI: 10.3390/plants10010166.

Lowe A, Norris AC, Farris AJ, Babbage DR. 2018. Quantifying thematic saturation in qualitative data analysis. Field Methods 30 (3): 191-207. DOI: 10.1177/1525822X17749386.

Majola NG, Gerrano AS, Shimelis H. 2021. Bambara groundnut (*Vigna subterranea* [L.] Verdc.) production, utilisation and genetic improvement in Sub-saharan Africa. Agronomy 11 (7): 1345. DOI: 10.3390/agronomy11071345.

Maphosa Y, Jideani VA, Maphosa L. 2022. Bambara groundnut production, grain composition and nutritional value: Opportunities for improvements. J Agric Sci 160 (6): 448-458. DOI: 10.1017/S0021859622000521.

Mayes S, Ho WK, Chai HH, Gao X, Kundy AC, Mateva KI, Zahrulakmal M, Hahiree MKIM, Kendabie P, Licea LCS, Massawe F, Mabhaudhi T, Modi AT, Berchie JN, Amoah S, Faloye B, Abberton M, Olaniyi O, Azam-Ali SN. 2019. Bambara groundnut: An exemplar underutilised legume for resilience under climate change. Planta 250 (3): 803-820. DOI: 10.1007/s00425-019-03191-6.

Mbosso C, Boulay B, Padulosi S, Meldrum G, Mohamadou Y, Niang AB, Coulibaly H, Koreissi Y, Sidibé A. 2020. Fonio and bambara groundnut value chains in Mali: Issues, needs, and opportunities for their sustainable promotion. Sustainability 12 (11): 4766. DOI: 10.3390/su12114766.

Mubaiwa J, Fogliano V, Chidewe C, Linnemann AR. 2018. Bambara groundnut (*Vigna subterranea* (L.) Verdc.) flour: A functional ingredient to favour the use of an unexploited sustainable protein source. PLoS One 13 (10): e0205776. DOI: 10.1371/journal.pone.0205776.

Paliwal R, Abberton M, Faloye B, Olaniyi O. 2020. Developing the role of legumes in West Africa under climate change. Curr Opin Plant Biol 56: 242-258. DOI: 10.1016/j.pbi.2020.05.002.

Qadir A. 2012. Pemodelan Pertumbuhan Tanaman Kedelai (*Glycine max* (L.) Merrill) Dibawah Cekaman Naungan [Disertasi]. Institut Pertanian Bogor, Bogor. [Indonesian]

Sari M, Ilyas S, Suhartanto MR, Qadir A. 2021. Pre-harvest sprouting on high-level seed dormancy of Bambara groundnut (*Vigna subterranea*) landraces. Biodiversitas 22: 5617-5623. DOI: 10.13057/biodiv/d221247.

Tan XL, Azam-Ali S, Von Goh E, Mustafa M, Chai HH, Ho WK, Mayes S, Mabhaudhi T, Azam-Ali S, Massawe F. 2020. Bambara groundnut: An underutilized leguminous crop for global food security and nutrition. Front Nutr 7: 601496. DOI: 10.3389/fnut.2020.601496.

Unigwe AE, Gerrano AS, Adebola P, Pillay M. 2016. Morphological variation in selected accessions of bambara groundnut (*Vigna subterranea* L. Verdc) in South Africa. J Agric Sci 8 (11): 69-80. DOI: 10.5539/jas.v8n11p69.