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RESEARCH ARTICLE

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Expected yield and economic improvements of a yam seed system in West Africa using agro-physiological modelling

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Societal Impact Statement

Yam is a major tropical root crop and a staple food for millions of people in West Africa. The model used in this study shows that promoting the use of improved seed tubers would help increase yields and profitability for farmers. This could lead to improved food security, increased income and higher standards of living. Additionally, the model serves as a useful decision-support tool for farmers and technicians to choose, depending on the species, the optimum seed-tuber weight and planting date. This study provides agronomic arguments to justify investments in the improvement of yam planting materials in West Africa.

Summary

- Yam (*Dioscorea* spp.) is a major tropical root crop, grown mainly in West Africa using traditional extensive techniques. Farmers typically reuse seed tubers by setting aside up to 30% of their production for the next season, leading to high planting material variability that affects yields. Several initiatives aim to promote the use of improved seed tubers. However, to help their adoption, it is necessary to quantify the agronomic and economic advantages.
- To address this, a model for individual plant growth and development was developed based on six experiments in Benin from 2007 to 2009. This model simulates the combined effect of emergence (through photoperiod and temperature) and seed-tuber weight on yam plant growth and development. Its predictions were highly correlated with observed plant tuber yield (R^2 > 0.83).
- Results highlight the crucial role of key processes such as seed-tuber physiological age and photoperiod sensitivity. The study shows that for the traditional planting dates, the use of improved planting material could lead to a yield increase of 22%–27% and a gain in profitability of 30% and 40% for *Dioscorea alata* and *Dioscorea rotundata*, respectively. The model proved to be a useful decision-support tool for choosing an optimum seed-tuber weight, depending on the species and the planting date.
- This study validates investments in yam seed systems in West Africa. However, beyond seed size and health, other factors such as dormancy, storage time and

their management need to be considered to address emergence heterogeneity and its impact on yield.

KEYWORDS
Dioscorea spp, photoperiod, plant model, seed-system, vegetatively propagated crop, West Africa

1 | INTRODUCTION

Yam (*Dioscorea* spp.) production is the third most important tropical root crop after cassava and sweet potato. Most of the world's production comes from West Africa, where its gross production value in 2021 ranks first, far before cassava, maize and rice (FAOSTAT, 2023). Yam production is based on traditional low-density planting and extensive practices. Planting takes place at the beginning of the rainy season, between February and May, depending on the onset of rain and the farmer's calendar (Orkwor et al., 1998). Traditionally, farmers either plant whole small tubers left over from ware yam production or cut large tubers into smaller pieces of the desired size, usually between 250 and 1000 g (Aighewi et al., 2020). In this way, up to 33% of yams otherwise available for human consumption are reserved for planting new crops (Orkwor et al., 1998). If, as several studies have shown, seed-tuber size positively influences aerial growth during the vegetative phase and consequently leads to higher tuber yield, the economic optimum may change depending on the planting date and expected yield (Cornet et al., 2016; Ferguson, 1973; Okoli et al., 1999).

Traditional practices also result in highly variable planting material, whether in size, physiological age or nutrient content (Cornet et al., 2016). Uncontrolled physiological age and size of seed tubers can affect emergence time (Cornet et al., 2016; Orkwor et al., 1998). Cornet et al. (2016) showed that traditional West African cropping systems have a serious drawback in terms of the uncontrolled wide range of physiological ages and reserves in seed-tuber lots, which affects the plant size hierarchy and ultimately the marketable yield. Cornet et al. (2014) showed that even equally sized traditional planting material may emerge unevenly, resulting in individual plant size variation and high inter-plant yield variability. The crop model explained these phenomena by the photoperiod sensitivity of yam, which delays emergence, resulting in a shortened vegetative phase, reduced leaf area and consequently lower yield potential (Marcos et al., 2009).

For these reasons, improving yam agricultural productivity is significantly hampered by the lack of access to high-quality planting material, which is often cited as the most pressing challenge (Mignouna et al., 2020). Worldwide, seed production systems have significantly improved the production of potatoes (*Solanum tuberosum*), mainly through better control of virus transmission and improved earliness and homogeneity of emergence (Forbes et al., 2020; Knowles & Botar, 2011). Despite compelling evidence, the actual cost of using heterogenous yam seed tubers, or, in simpler terms, the anticipated advantage of using better planting materials, remains uncertain. In a prospective study, Mignouna et al. (2020) estimated that adaptive yam miniset, an improved planting material production technique, could significantly reduce poverty for more than 250,000 people out of more than 28 million potential beneficiaries in West Africa. However, this study is based on expert opinion and lacks agronomic evidence.

The objective of this study was to investigate the agronomic and economic benefits of reducing variability in emergence dates through a theoretically improved seed system. To achieve this objective, a simple and descriptive model of individual yam growth and development was used to simulate yield as a function of traditional emergence dates and seed-tuber size ranges. These simulations were used to compare the behaviour of the two main yam species in West Africa (i.e., *Dioscorea rotundata* and *Dioscorea alata*) under two planting material scenarios: traditional and improved. Finally, the profitability of traditional and improved planting materials was estimated.

2 | MATERIALS AND METHODS

2.1 | Data sets

The dataset used here comes from six experiments carried out between 2007 and 2009 at two sites in Benin (West Africa): AfricaRice Cotonou Station (6°25′ N, 2°19′ E, 23 m asl) and Glazoue (7°56′ N, 2°15′ E, 200 m asl). Both sites are located in the transition zone between forest and savannah. The climate is sub-equatorial with a bimodal rainfall pattern, mainly from March to July and from September to October. The soils used in this study are arenosols (FAO-ISRIC-ISSS, 1998) with good physical properties but low nutrient levels. The field trials consisted of 300–550 plants. All trials followed traditional planting systems used in West Africa. Small whole seed tubers from traditional farmers' planting material, weighing between 220 and 600 g, were planted in mounds without stakes at a density of 0.7 plant/m^2. For each experiment, the seed tuber lot came from a single farm plot in order to reflect the variability in size, physiological age and nutrient concentration that exists at the farmer level.

Two well-known local cultivars representing the two main species were selected: ‘Florido’ for *D. alata* and ‘Morokorou’ for *D. rotundata*. Morokorou is a traditional early-maturing variety from northern Benin, producing 1–3 cylindrical tubers. Florido was introduced to West Africa from Puerto Rico in the early 1970s and produces two to five round tubers (Doumbia et al., 2004). The planting dates were February 20, 2007, March 25, 2009 and April 25, 2008. The trials in Glazoue were not irrigated, but in Cotonou, the crop was irrigated to field capacity at planting, and further supplemental irrigation (totalling between 80 and 110 mm depending on the growing season) was applied to replace estimated evapotranspiration using overhead sprinklers until mid-November. Plants showed no visual signs of water or nutrient stress. Weed control was carried out by hand every 2 weeks. For more information on the sites or agricultural practices, see Cornet et al. (2016).

Individual plant emergence dates were recorded every 3 days in all trials until the final plant stand was established. We defined individual emergence as the emergence of tuber shoots from the soil. Plants were sampled from an area of 1.5–3 m^2 every 2–3 weeks for leaf and stem biomass and leaf area from emergence to tuber maturity. There were four replicates of two plants at each sampling date. The leaf area in 2007 trials was estimated using allometric relationship (Cornet et al., 2015). In the 2008 and 2009 Cotonou trials, leaf area was measured using a planimeter (Li-Cor model 3100, LI-COR Inc., Lincoln, NE, USA). Leaf, stem and tuber biomass was determined after 72 h of drying at 70°C. Daily minimum and maximum air temperatures were measured at a standard meteorological station located less than 500 m from the plots. The mean daily temperature (T) was calculated as the average of the daily minimum and maximum temperatures. Astronomical day length, including twilight, was calculated according to Keisling (1982).

2.2 | Yam individual plant model

The model is divided into a phenology module and a growth module. Yam phenology was divided into two main phases (Marcos et al., 2009): emergence to tuber initiation (EM-TI) and tuber initiation to harvest (TI-HA). The duration of both phases is estimated based on a simplified version of the CropSyst Yam model (Marcos et al., 2009; Marcos et al., 2011), taking into account photoperiod and thermal sensitivity. This cumulative method implies that the plant progresses daily towards tuber initiation or maturity at a variable rate depending on temperature and photoperiod. As there is traditionally no irrigation in the yam fields of West Africa, an additional constraint was added to the model, stopping further growth at the end of the rainy season (i.e., mid-November). A detailed description of the phenology module of the model is given in Notes S1.

Previous studies have shown that the maximum leaf area index is reached soon after tuber initiation (Campbell et al., 1962; Marcos et al., 2011; Sobulo, 1972). We assumed that tuber weight (TW, g/plant) increased proportionally to leaf area index at tuber initiation (LA_{TI}, m^2/plant):

$$TW = \beta LA_{TI} (HA - TI), \tag{1}$$

where HA and TI are the harvest and tuber initiation dates, and β is a constant.

Leaf area at tuber initiation was assumed to be proportional to the length of the vegetative phase (EM-TI), defined as the time between emergence and tuber initiation:

$$LA_{TI} = \gamma (TI - EM), \tag{2}$$

where EM is the date of emergence and γ is a constant that determines the leaf area growth rate (m^2/day).

Several studies have shown that plants from smaller seed tubers accumulate dry matter and develop leaf area at a much slower rate than others (Cornet et al., 2014; Nwoke et al., 1973; Onwueme, 1972). As seed-tuber weight (SW) in farmers' planting material is not uniform, its influence on vegetative growth was also included in the model. As shown in previous works, a positive asymptotic relationship between γ and SW (g/plant) was used (Ferguson, 1973; Rodriguez-Montero et al., 2001). In the present study, this asymptotic relationship was defined by a modified Gompertz curve with biologically meaningful parameters (Hunt, 1982).

$$\gamma = \varepsilon e^{-e^{(\delta*(250-\mathrm{SW}))}}, \tag{3}$$

where δ is the relative growth rate at an inflection point, and ε is a proportionality constant. The abscissa of the inflection point was set at 250 g, corresponding to the SW required to obtain one-third of the maximum plant yield found by Ferguson (1973).

Combining Equations (1), (2) and (3), the plant TW is calculated as follows:

$$\mathrm{TW} = \varepsilon e^{-e^{(\delta*(\sigma-\mathrm{SW}))}} (\mathrm{TI} - \mathrm{EM})(\mathrm{HA} - \mathrm{TI}). \tag{4}$$

By combining Equation (4) and phenophase duration, it is possible to estimate the plant tuber yield for a given harvest date. The estimation of the model parameters is described in detail in Notes S2.

2.3 | Crop simulation with and without improved planting material

Because there is no inter-plant competition at traditional planting densities in West African yam fields (Cornet et al., 2014), it was possible to simulate the crop yield as the sum of the predicted individual plant yields. To determine the consequences of using heterogeneous planting material, the yield achievable from traditional and improved planting material was simulated. The simulated distribution of traditional planting material was characterised by a wide range of emergence dates and variable SWs, while the distribution of improved planting material was characterised by a narrower range of emergence dates and more uniform SWs.

SW and emergence distributions for the traditional planting material were defined from six trials conducted in Benin (Cornet et al., 2014), while the improved treatment characteristics were based on similar observations of the improved potato seed system (Beattie, 2010; Knowles & Botar, 2011; O'Brien et al., 1983). In the traditional cropping system, Cornet et al. (2014) observed a normal distribution of SW and a gamma distribution of emergence, with shape and scale parameters equal to two (left skewed). The characteristics (mean and standard deviation) of the traditional and improved planting materials are presented in Table 1. The climatic variables (i.e., temperature, photoperiod and rate of change of photoperiod) are those measured in 2009 in Cotonou, Benin.

2.4 | Profitability of traditional and improved planting material

A rough estimate of the profitability of both traditional and improved planting material was calculated for successive planting dates and varying seed-tuber sizes. In West Africa, tubers are sold on a cash-and-carry basis, and prices are mainly based on variety, season and, for *D. rotundata*, perceived tuber size (Orkwor et al., 1998). The profit was calculated as the proceeds from the sale of the tubers minus the cost of the seed tubers. The selling prices of both species were recorded weekly at the yam market in Glazoue (Benin) for 3 years and averaged. For *D. rotundata*, different prices were recorded for large (>2.5 kg) and small tubers (0.8–2.5 kg). As yams are sold in Benin by volume (in basins or in heaps), the tubers were weighed to obtain the price per kilo (€/kg). Figure 1 shows the average selling prices over three growing seasons. A peak can be seen in June/July when the tubers from the previous season start to become less available on the market due to their limited shelf life. The tuber size category was derived from the estimated individual plant tuber yield from the plant model. The date of sale was estimated from the model using the end of the tuberisation phase as the maturity date. The cost of the seed tuber was calculated on the basis of its weight in relation to its quality, as commonly practised in the seed tuber market (Kleih et al., 2012; Ogbonna et al., 2011).

3 | RESULTS

3.1 | Plant model validation

The estimated and observed values of the model outputs were analysed. Figure 2 presents (i) the relationship between observed plant leaf area and the submodel vegetative index (SVI, eq. 6 in Notes S2) predictions of the model and (ii) the relationship between the predicted and observed plant yield. This double check of the model was necessary because of the significant risk of overfitting given the large number of parameters used in the optimisation process and the many variables used in the model. To check the appropriateness of the model components, the observed leaf area index was used to test the vegetative part of the model (Figure 2a,b). The leaf area of the sampled plants varied between 0 and 1.6 m^2/plant. A coefficient of determination always higher than 0.72 was observed. The relationship between observed and predicted plant tuber yield of the two main yam species is shown in Figure 2c,d. Yams yielded up to 1500 and 2000 g of tuber dry matter per plant for *D. alata* and *D. rotundata*, respectively. The species-specific models gave good estimates of the observed plant tuber yield (both R^2 > 0.83). No systematic bias was found.

The mean temperature during the growing season varied between 20.4 and 30.5°C (Figure 3a). The photoperiod varied between 12.5 and 13.3 h (Figure 3b). Figure 3c,d shows the influence of emergence date on the duration of EM-TI and TI-HA growth stages as a function of temperature and day length. Most emergence occurred at a time of increasing day length. Within this range of

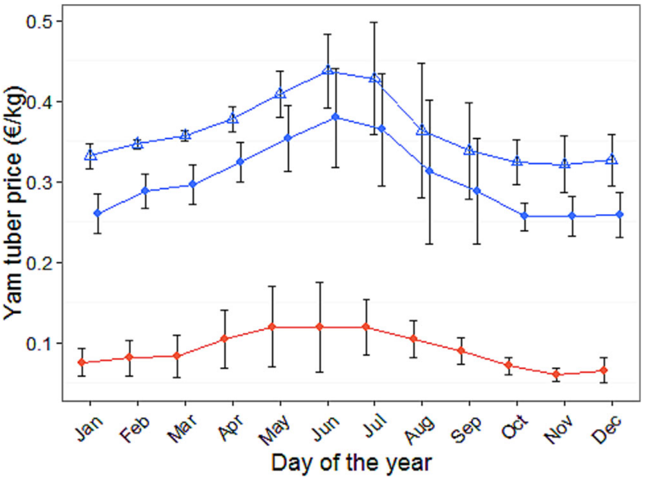

FIGURE 1 The selling prices of yams (*Dioscorea alata* [red] and *Dioscorea rotundata* [blue]) at the market of Glazoue (Benin) depending on the size of the tuber (circle: tuber over 2.5 kg; triangle: tuber between 0.8 and 2.5 kg). Error bars are standard deviation of mean price over the three growing seasons.

TABLE 1 Characteristics of the distributions of yam (*Dioscorea* spp.) emergence and seed-tuber size used to compare the effect of traditional and improved planting material on plant growth, development and yield.

Factor	Distribution	Level	Mean	SD	IQR90	Min	Max
Emergence (days after planting)	Gamma	Traditional	27	19.8	67	2	100
		Improved	8	6.2	20	2	30
Seed-tuber size (g/plant)	Normal	Traditional	400	50.6	140	255	533
		Improved	400	5.3	20	389	416

Abbreviations: IQR90, 90% interquartile range; SD, standard deviation.

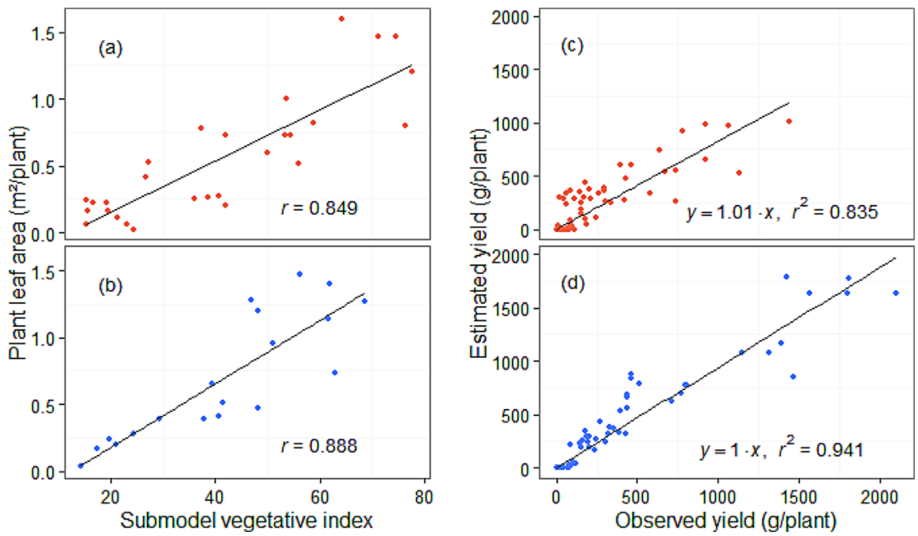

FIGURE 2 The modelled and observed effects of environmental variables and planting material characteristics on yam (*Dioscorea* spp.) plant. Estimated against observed outputs of best model components: plant leaf area of *Dioscorea alata* (a) and *Dioscorea rotundata* (b), and plant yield of *D. alata* (c) and *D. rotundata* (d) as influenced by temperature and daylength from plant emergence.

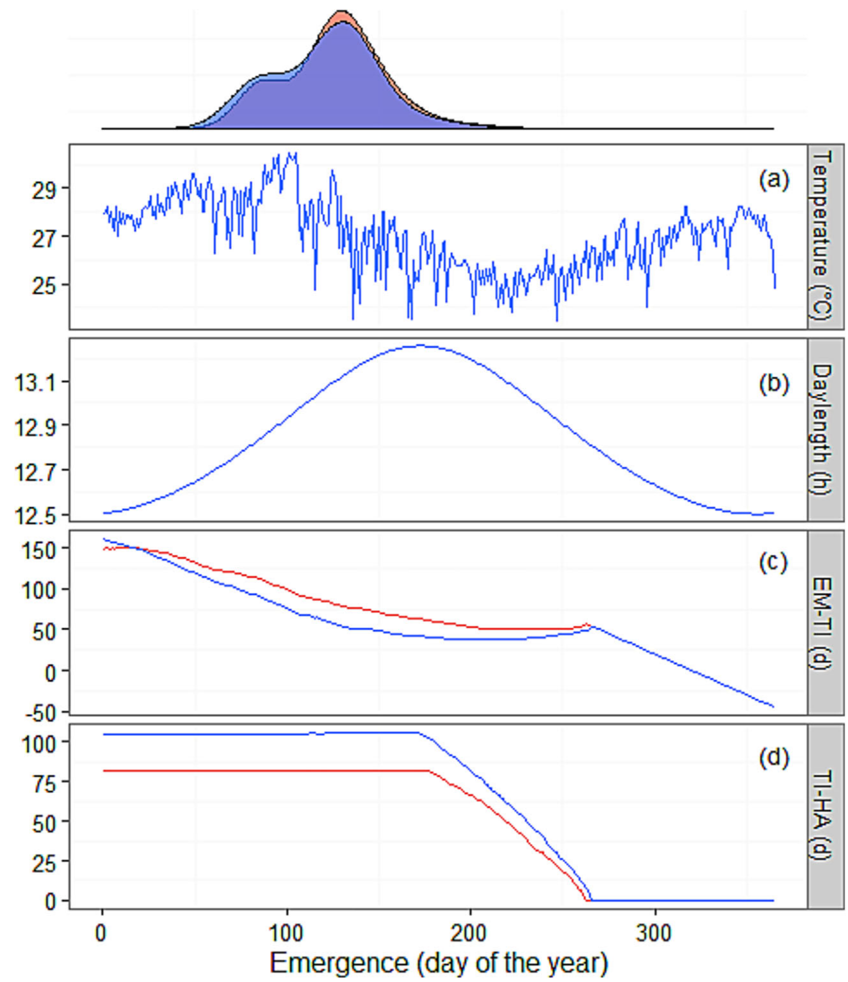

FIGURE 3 Modelling the influence of environmental parameters on yam (*Dioscorea* spp.) individual plant phenology. Temperature (a), photoperiod (b) and estimated growth phenology stage durations (c and d) as a function of emergence date of the two main yam species: *Dioscorea alata* (red) and *Dioscorea rotundata* (blue). Emergence to tuber initiation (EM-TI) is the vegetative phase, and tuber initiation to harvest (TI-HA) the tuberization phase. The density plot at the top of the figure presents the density function of the observed emergence dates of both yam species within the six experiments of the current study.

emergence, the vegetative phase occurred during a warmer period than the tuberisation phase. *D. alata* always had a longer vegetative phase and a shorter tuberisation phase than *D. rotundata*. Emergence later than the end of June (i.e., the 180th day of the year) resulted in a sudden decrease in the duration of the tuberisation phase (TI-HA).

3.2 | Simulated crop yield

Figure 4a compares the simulated yields of both yam species using traditional and improved planting materials. Both simulated and observed yields decreased with successive planting dates. The

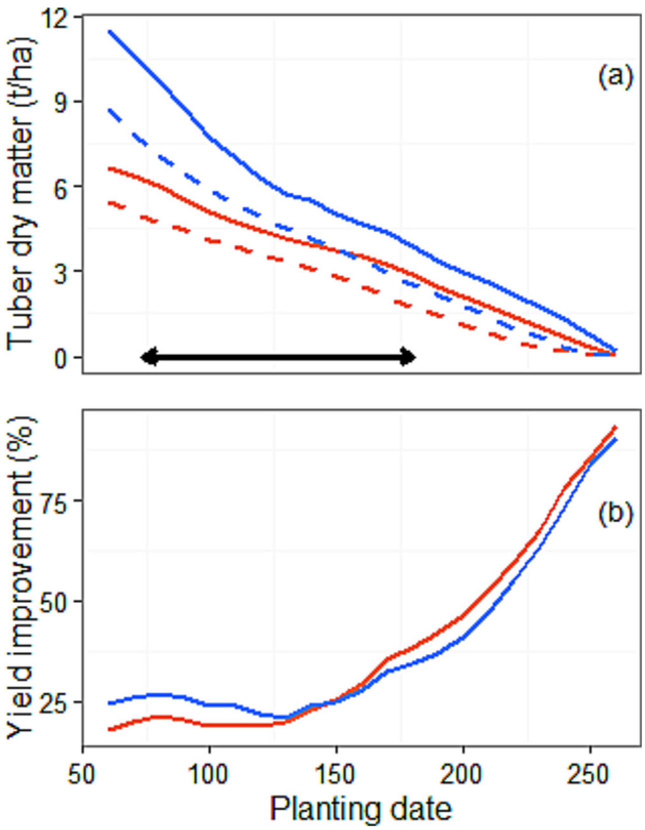

FIGURE 4 Influence of the planting date on the estimated yield differences between improved (solid line) and traditional (dashed line) cropping systems of the two main yam species grown in West Africa (*Dioscorea alata* in red and *Dioscorea rotundata* in blue). The black arrow indicates the traditional planting date in West Africa.

simulated yield of *D. rotundata* was always higher than that of *D. alata*, but this difference tended to decrease with later planting dates. Within the range of traditional planting dates, the yield improvement due to narrower emergence spread and uniform SW was always more than 18% (Figure 4b). For early planting dates (i.e. before 150 days), the yield improvement is relatively stable and higher for *D. rotundata* than for *D. alata* (i.e. 24 ± 2.1% and 20 ± 1.5% yield increase, respectively). Thereafter, the positive effect of using improved planting material increased significantly, although this was mainly due to lower tuber dry matter production.

The comparison of tuber dry matter yield (t/ha) of both species in the traditional cropping system as a function of planting date and SW is shown as a contour plot in Figure 5a,b. For a given planting date and SW, *D. rotundata* always outperformed *D. alata*, for example, at 110 days with an SW of 550 g, the yields in the traditional cropping system were 6.9 and 5.9 t/ha of tuber dry matter, respectively. In general, the later the planting date, the lower the yield, while the heavier the tuber, the higher the yield. In parallel, the yield gain attributable to SW decreased with later planting dates; for example, for *D. alata* in the traditional cropping system (Figure 5a), doubling the SW from 250 to 500 g increased the yield by 3.0 t/ha with a planting date of 90 days, whereas with a later planting date of 180 days, doubling the SW increased the yield by only 1.2 t/ha. The yield increase in tuber dry matter (t/ha) due to the use of improved planting material is shown in Figure 5c,d. It varied between 0.3 and 1.4 t/ha for *D. alata* and between 0.4 and 2.8 t/ha for *D. rotundata*.

3.3 | Profitability of traditional and improved planting material

The profit of the traditional cropping system, calculated as income from harvest sales minus seed-tuber costs (k€/ha), was estimated for *D. rotundata* and *D. alata* (Figure 6a,b). Within the validity range of the models, the profitability of early planting (i.e., March) increased with increasing SW, reaching 1.7 and 8.5 k€/ha for *D. alata* and *D. rotundata*, respectively. Profit decreased with delayed planting (reaching zero after 180 days), but particularly rapidly when large tubers were used. The use of improved planting material was always followed by an increase in profitability (Figure 6c,d). This gain was much higher with higher SW and early planting (up to 0.5 and 3 k€/ha for *D. alata* and *D. rotundata*, respectively). In both absolute and relative terms, profitability was always higher for *D. rotundata*. In fact, the average increase in profitability compared with the traditional planting dates was 30% and 40% for *D. alata* and *D. rotundata*, respectively.

4 | DISCUSSION

4.1 | Model performance

Within the range of the experimental data, this individual plant model provided a good estimate (low root mean square error and high correlation with observed data) of the duration of the growth stages and of the plant yield for both species. The cardinal temperatures of *D. alata* were similar to those found by other authors: that is, the minimum, optimum and maximum temperatures in the current study were 11.1, 19.3 and 29.1°C, against 12.3, 19.7 and 32.5°C in the study by Marcos et al. (2009). The corresponding values during the vegetative phase were 10.4, 26.8 and 42.6°C compared with 17.2, 28.3 and 42.3°C. For *D. rotundata*, there is only one study in which the cardinal temperatures were estimated for the whole vegetative period (Ile et al., 2007), in which 12°C was found to be the minimum temperature and 25.8°C the optimum temperature. The same authors found the maximum temperature to be the same as that of cassava (i.e., 42°C). The results of the current study were in the same range.

Both species showed a photoperiod response to growth phase duration characteristics of short-day plants. The critical photoperiod threshold for *D. alata* was close to that found by Marcos et al. (2009) during the vegetative phase (i.e., 12.7 h against their 12.8 h). Because of methodological differences in the estimation of the critical photoperiod, the results obtained by Ile et al. (2007) for *D. rotundata* are not comparable. The photoperiod sensitivity of *D. alata* was much higher than that of *D. rotundata*. The high sensitivity of *D. alata* is in agreement with the result of Marcos et al. (2009) and with common

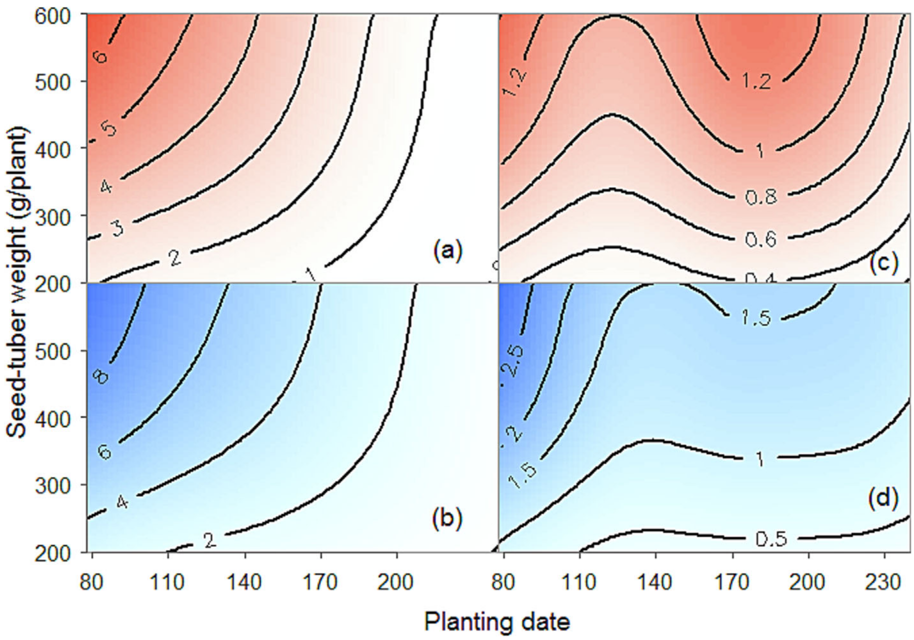

FIGURE 5 Yield (a–b, tonnes of tuber dry matter per hectare) of the traditional cropping system for *Dioscorea alata* (red) and *Dioscorea rotundata* (blue) and yield improvement linked to the use of improved planting material (c–d) as a function of planting date and seed-tuber weight. Contour lines represent level of equal yield or yield improvement.

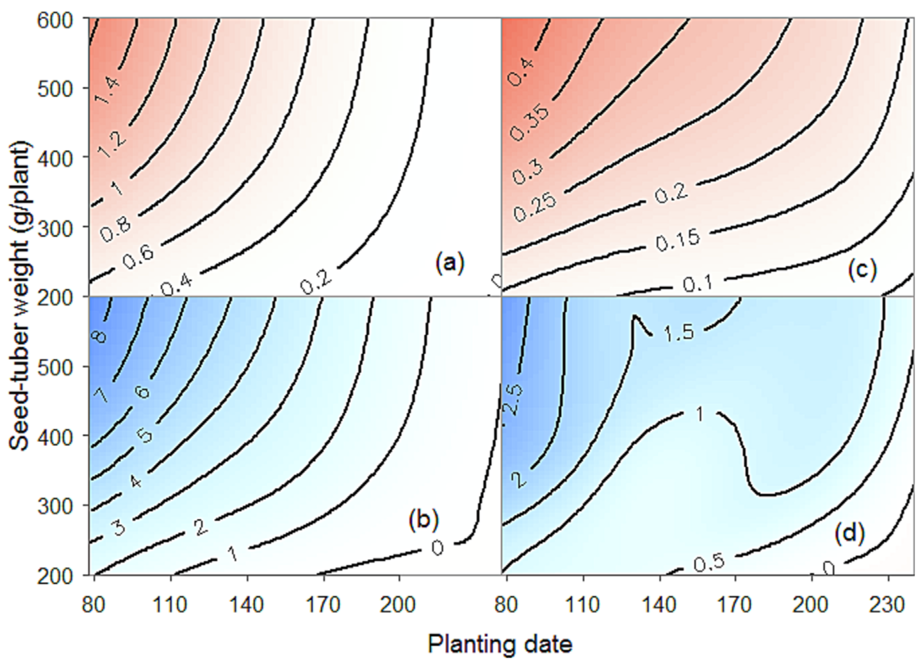

FIGURE 6 Profitability (a–b, in k€ per hectare) of the traditional cropping system for *Dioscorea alata* (red) and *Dioscorea rotundata* (blue) and profitability improvement linked to the use of improved planting material for *D. alata* and *D. rotundata* (c–d) as a function of planting date and seed-tuber weight. Contour lines represent level of equal profitability and profitability improvement.

practices in the Caribbean, where *D. alata* cannot be grown out of season, whereas *D. rotundata* can.

The higher simulated yield of *D. rotundata* over *D. alata* is in accordance with the observed yields over the three growing seasons and the two sites of this study. However, *D. alata* is known to have a higher yield than *D. rotundata*. This discrepancy could be due to the higher dry matter content of *D. rotundata* (Otegbayo et al., 2023), but also to its higher performance under good growing conditions, that is, planting after long fallow without abiotic stress (Orkwor et al., 1998).

The observed and simulated influence of SW on crop yield was significant for both species (i.e., average δ of 0.0065, indicating a 57% yield increase for SWs ranging from 250 to 550 g). This result for *D. rotundata* is in agreement with previous studies (Nwoke et al., 1973; Onwueme, 1972; Oriuwa & Onwueme, 1980). For *D. alata*, this important effect of SW up to 550 g was not observed by Ferguson (1973), who found no significant benefit of increasing SW beyond 400 g. This discrepancy could be explained by some confounding effects. Whereas Ferguson (1973) used cut pieces of whole tubers, this study used whole seed tubers from the previous growing season. Thus, smaller seed tubers may have come from weaker plants. The observed adverse effect of smaller seed-tuber weight may have been confounded by lower-quality tubers from the previous cropping season (i.e., lower nutrient or dry matter content).

4.2 | Simulation of yam plant growth and development

At traditional planting dates, emergence occurs at a time of increasing day length. Within this emergence period, the vegetative phase occurred during a warmer period than the tuberisation phase. As the cardinal temperatures of both species are lower during the vegetative phase than during the tuberisation phase, shifting the planting date to a cooler period (May–June) could lead to improved yields for less photoperiod-sensitive varieties in irrigated cropping systems. An off-season yam production trial was carried out in a farmer's field in an inland valley in Niger State, Nigeria (Shiwachi et al., 2008). In their study, the cultivars tested belonged to *D. alata* and produced a low yield for which no explanation was given. In the future, the use of low photoperiod sensitive cultivars of *D. rotundata* could be a solution.

The minimum lengths of both vegetative and tuberisation growth phases ($1/r_x$) were shorter for *D. alata* than for *D. rotundata*, in line with current knowledge of yam physiology (Orkwor et al., 1998; Sartie et al., 2012). The values of r_x for *D. alata* were in agreement with a previous study (Marcos et al., 2009). Despite a shorter minimum vegetative phase ($1/r_x$), *D. alata* always had a longer simulated vegetative phase than *D. rotundata*. This could be explained by its greater sensitivity to the photoperiod, which delayed the onset of tuber formation until the critical threshold of the photoperiod. While the tuberisation growth phase of both species is constant for planting dates up to the end of June, the duration of the vegetative phase decreases asymptotically until it reaches a minimum for planting dates in July. The decreasing duration of the vegetative phase with delayed emergence is explained by the influence of both photoperiod and temperature. Later, a sudden decrease in the duration of the tuberisation phase was estimated because the model imposes a constraint that prohibits growth beyond the beginning of the dry season.

4.3 | Simulation of yam yield

Within the range of the experimental data and for an average SW of 400 g, the yield increase due to the use of improved planting material was always more than 18% and could reach up to 40% depending on the species and planting date. Considering the influence of both planting date and seed-tuber weight, the yield increase associated with improved practices varied between 0.3 and 1.4 t of tuber dry matter per hectare for *D. alata* and between 0.4 and 2.8 t for *D. rotundata*.

The yield advantage of *D. rotundata* over *D. alata* was complemented by its much higher selling price (up to three times higher). This was evident when looking at the profitability of both species (up to 1.7 and 8.5 k€ for *D. alata* and *D. rotundata*, respectively, in traditional cropping systems). Despite the higher cost of increasing the weight of the seed tuber, the use of larger seed tubers was still profitable. This advantage decreased when planting was delayed. The considerable advantage of increasing SW up to more than 600 g may explain the lack of adoption of some innovative techniques (e.g., minisets).

For traditional planting dates, the use of improved planting material increased simulated profitability by an average of 30% and 40% for *D. alata* and *D. rotundata*, respectively. For *D. rotundata*, the large seasonal price variation made the contours of the profitability gain more complex. Linking the model to a market information system could help the farmer choose the best options before planting and at harvest regarding the possibility of storing the crop. The model could also be used as a decision-support tool for farmers, allowing them to choose the best SW depending on the species and planting date. Finally, the model helps shed new light on a farming practice that, at first glance, seems surprising to agronomists. The very low planting densities traditionally practised in West Africa allow for optimal plant development, free from competition, leading to maximisation of individual plant yield. The deliberate choice to favour individual plants rather than yield per unit area is due to consumer preference for large tubers, which fetch higher prices.

The use of this model is limited to West African cropping systems where there is no competition between neighbouring plants. Higher-density cropping systems (e.g., in the Caribbean) are likely to be subject to some inter-plant competition that reduces the yield of individual plants. Further work is needed to extend the validity of the model, in particular to take account of potentially more profitable out-of-season cropping.

The role of pests and diseases was not considered in this study. It is therefore likely that the benefits of establishing a seed production system are underestimated if the production of healthy material is taken into account. As with most vegetatively propagated crops, pests and diseases of yam can be spread by the seed tuber (mainly nematodes and viruses). The use of techniques that produce healthy material leads to additional production gains (Morse, 2021). However, incorporating the costs and benefits of this type of technique into the current model requires dedicated work to take into account the possible physiological peculiarities of this type of planting material and their consequences for yam plant growth and development.

Currently, there are some projects dealing with improved yam seed-tuber production in West Africa (e.g., the Yam Improvement for Income and Food Security in West Africa project or the AfricaYam project; Maroya et al., 2022). They focus mainly on the production of fast, clean (healthy) seed yam, for example by using temporary immersion bioreactors and aeroponic or hydroponic systems. The results of this study help to legitimise recent investments in yam seed systems in West Africa. But they also point to the need to improve more than just seed size and health. Indeed, physiological age and its impact on emergence heterogeneity also need to be addressed by including variables such as dormancy, storage time and the means to manage them. In addition, seed-tuber production systems could also control varietal purity, another known source of variability in vegetatively propagated root and tuber crops (Chair et al., 2010; Elias et al., 2001).

AUTHOR CONTRIBUTIONS

Denis Cornet, Jorge Sierra and Benoît Gabrielle planned and designed the research. Denis Cornet, Jorge Sierra, Komivi Dossa and Régis

Tournebize performed experiments, conducted fieldwork, analysed data, and so forth. All authors wrote the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Aighewi, B., Maroya, N., Asiedu, R., Aihebhoria, D., Balogun, M., & Mignouna, D. (2020). Seed yam production from whole tubers versus minisetts. *Journal of Crop Improvement*, *34*(6), 858–874. https://doi.org/10.1080/15427528.2020.1779157

Beattie, B. M. (2010). The effects of seed production practices on the productivity of the succeeding ware potato crop. PhD thesis, University of Tasmania. https://eprints.utas.edu.au/14538/

Campbell, J. S., Chukwueke, V. O., Teriba, F. A., & Ho-A-Shu, H. S. V. (1962). Some physiological investigations into the White Lisbon yam (*Dioscorea alata* L.) II. Growth period and out-of-season production. *Empire Journal of Experimental Agriculture*, *30*, 232–238.

Chair, H., Cornet, D., Deu, M., Baco, M. N., Agbangla, A., Duval, M. F., & Noyer, J. L. (2010). Impact of farmer selection on yam genetic diversity. *Conservation Genetics*, *11*, 2255–2265. https://doi.org/10.1007/s10592-010-0110-z

Cornet, D., Sierra, J., & Tournebize, R. (2015). Assessing allometric models to predict vegetative growth of yams in different environments. *Agronomy Journal*, *107*(1), 241–248. https://doi.org/10.2134/agronj14.0370

Cornet, D., Sierra, J., Tournebize, R., Gabrielle, B., & Lewis, F. I. (2016). Bayesian network modeling of early growth stages explains yam interplant yield variability and allows for agronomic improvements in West Africa. *European Journal of Agronomy*, *75*, 80–88. https://doi.org/10.1016/j.eja.2016.01.009

Cornet, D., Sierra, J., Tournebize, R., & Ney, B. (2014). Yams (*Dioscorea* spp.) plant size hierarchy and yield variability: Emergence time is critical. *European Journal of Agronomy*, *55*, 100–107. https://doi.org/10.1016/j.eja.2014.02.002

Doumbia, S., Tshiunza, M., Tollens, E., & Stessens, J. (2004). Rapid spread of the Florido yam variety (*Dioscorea alata*) in Ivory Coast: Introduced for the wrong reasons and still a success. *Outlook on Agriculture*, *33*(1), 49–54. https://doi.org/10.5367/000000004322877773

Elias, M., Penet, L., Vindry, P., Mckey, D., Panaud, O., & Robert, T. (2001). Unmanaged sexual reproduction and the dynamics of genetic diversity of a vegetatively propagated crop plant, cassava (*Manihot esculenta* Crantz), in a traditional farming system. *Molecular Ecology*, *10*, 1895–1907. https://doi.org/10.1046/j.0962-1083.2001.01331.x

FAOSTAT. (2023). Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database. [Rome]:FAO, 2023. Accessed August 2023.

Ferguson, T. U. (1973). The effect of Sett characteristics and spacing on growth, development and yield of yams (*Dioscorea* spp). PhD thesis, University of the West Indies, St Augustine, West Indies.

Forbes, G. A., Charkowski, A., Andrade-Piedra, J., Parker, M. L., & Schulte-Geldermann, E. (2020). Potato seed systems. In H. Campos & O. Ortiz (Eds.), *The potato crop*. Springer. https://doi.org/10.1007/978-3-030-28683-5_12

Hunt, R. (1982). *Plant growth curves*. Edward Arnold Publisher.

Ile, E. I., Craufurd, P. Q., Asiedu, R., & Battey, N. H. (2007). Duration from vine emergence to flowering suggests a long-day or rate of change of photoperiod response in white yam (*Dioscorea rotundata* Poir.). *Environmental and Experimental Botany*, *60*, 86–94. https://doi.org/10.1016/j.envexpbot.2006.06.009

Keisling, T. C. (1982). Calculation of the length of day. *Agronomy Journal*, *74*, 758–759. https://doi.org/10.2134/agronj1982.00021962007400040036x

Kleih, U., Phillips, D., Mignouna, D., Ogbonna, M., & Siwoku, B. (2012). Nigeria—Scoping yam value chain analysis. In: Yam Improvement for Income and Food Security in West Africa, Final Report. IITA-NRI-NRCRI.

Knowles, N. R., & Botar, G. I. (2011). Modelling the effects of potato seed-tuber age on plant establishment. *Canadian Journal of Plant Science*, *71*(4), 1219–1232. https://doi.org/10.4141/cjps91-170

Marcos, J., Cornet, D., Bussiere, F., & Sierra, J. (2011). Water yam (*Dioscorea alata* L.) growth and yield as affected by the planting date: Experiment and modeling. *European Journal of Agronomy*, *34*, 247–256. https://doi.org/10.1016/j.eja.2011.02.002

Marcos, J., Lacointe, A., Tournebize, R., Bonhomme, R., & Sierra, J. (2009). Water yam (*Dioscorea alata* L.) development as affected by photoperiod and temperature: Experiment and modeling. *Field Crops Research*, *111*, 262–268. https://doi.org/10.1016/j.fcr.2009.01.002

Maroya, N., Balogun, M., Aighewi, B., Mignouna, D. B., Kumar, P. L., & Asiedu, R. (2022). Transforming yam seed systems in West Africa. In G. Thiele, M. Friedmann, H. Campos, V. Polar, & J. W. Bentley (Eds.), *Root, tuber and banana food system innovations*. Springer. https://doi.org/10.1007/978-3-030-92022-7_14

Mignouna, D. B., Akinola, A. A., Abdoulaye, T., Alene, A. D., Manyong, V., Maroya, N. G., Aighewi, B. A., Kumar, L. P., Balogun, M., Lopez-Montes, A., Rees, D., & Asiedu, R. (2020). Potential returns to yam research investment in sub-Saharan Africa and beyond. *Outlook on Agriculture*, *49*(3), 215–224. https://doi.org/10.1177/0030727020918388

Morse, S. (2021). The role of plant health in the sustainable production of seed yams in Nigeria: A challenging nexus between plant health, human food security, and culture. *Plant Pathology*, *71*(1), 43–54. https://doi.org/10.1111/ppa.13409

Nwoke, F. I. O., Njoku, E., & Okonkwo, S. N. C. (1973). The effect of size of seed yams on yield of individual plants of *Dioscorea rotundata*. In: International Symposium on Tropical Root Crops, Ibadan, Nigeria, 1973.

O'Brien, P. J., Allen, E. J., Bean, J. N., Griffith, R. J., Jones, S. A., & Jones, J. L. (1983). Accumulated day degrees as a measure of physiological age and the relationships with growth and yield in early potato varieties. *Journal of Agricultural Science, Cambridge*, *101*, 613–631. https://doi.org/10.1017/S002185960003865X

Ogbonna, M. C., Korieocha, D. S., Onyenobi, V. O., & Njoku, S. C. (2011). Profitability of minituber seed yam production technique in south east agro-ecological zone: Evidence from Abia state, Nigeria. *Journal of Agriculture and Social Research*, *11*, 113–119. https://www.ajol.info/index.php/jasr/article/view/78631

Okoli, O. O., Opara, M. U., & Anyoha, C. O. (1999). Effect of seed weight on yield determinants, yield components and intra-plot variability in

yield of yams (*Dioscorea* spp.). *African Journal of Root and Tuber Crops*, *3*, 44–48. https://eurekamag.com/research/004/421/004421746.php
Onwueme, I. C. (1972). Influence of weight of the planted tuber on the vegetative performance of white yam (*Dioscorea rotundata*, Poir.) plants. *Nigerian Agricultural Journal*, *9*, 170–173.
Oriuwa, L. O., & Onwueme, I. C. (1980). Determining the optimum spacing for growing yam (*Dioscorea* spp.) without stakes. *Quarterly Journal of International Agriculture*, *19*, 5–24.
Orkwor, G. C., Asiedu, R., & Ekanayake, I. J. (1998). *Food yams: Advances in research*. IITA and NRCRI.
Otegbayo, B. O., Tran, T., Ricci, J., & Gibert, O. (2023). *In situ* dynamic rheological analysis of raw yam tubers: A potential phenotyping tool for quality evaluation. *Journal of the Science of Food and Agriculture*. https://doi.org/10.1002/jsfa.12662
Rodriguez-Montero, W., Hilger, T. H., & Leihner, D. E. (2001). Effects of seed rates and plant populations on canopy dynamics and yield in the greater yam (*Dioscorea alata* L.). *Field Crops Research*, *70*, 15–26. https://doi.org/10.1016/S0378-4290(00)00145-3
Sartie, A., Franco, J., & Asiedu, R. (2012). Phenotypic analysis of tuber yield- and maturity-related traits in white yam (*Dioscorea rotundata*). *African Journal of Biotechnology*, *11*, 3964–3975. https://hdl.handle.net/10568/77427
Shiwachi, H., Kikuno, H., Fashola, R., & Asiedu, R. (2008). Enhancing off-season yam production in Nigeria. *African Journal of Agricultural Research*, *3*, 407–411. https://hdl.handle.net/10568/90795
Sobulo, R. A. (1972). Studies on white yam (*Dioscorea rotundata*). I. Growth analysis. *Experimental Agriculture*, *8*, 99–106. https://doi.org/10.1017/S0014479700005044

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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