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What kind of cotton ideotype is adapted to agroecological cropping systems and climate change in Benin?

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Abstract

Background Agroecological cropping systems are recognised as an alternative way to ensure the sustainability of cotton (*Gossypium hirsutum* L.) production in the context of climate change and degradation of soil fertility. A study was conducted in Benin from 2020 to 2023 to compare six different cotton cultivars in three agroecological cropping systems in two cotton-growing zones. Plough-based tillage plus incorporation of cover crop biomass (PTI), conservation agriculture with strip tillage (CA_ST), and conservation agriculture with no tillage (CA_NT) were compared with the reference plough-based tillage (PT). The objective was to identify morpho-physiological traits of cotton that increase yield in agroecological cropping systems. Our approach combined a field experiment and crop simulation model (CSM) of CROPGRO-Cotton to evaluate the effects of genotype (G) × environment (E) × management (M) interactions on seed cotton yield (SCY).

Results Cultivars Tamcot_camde and Okp768 and simulated ideotypes performed best in CA systems. Increased seed mass, large and thick leaves, and later maturity were identified as beneficial for yield enhancement in CA systems. Cultivars and ideotypes that combine these traits also resulted in better nitrogen and water use efficiencies in CA systems. Under different climate scenarios up to 2050, ideotypes designed could increase SCY in Benin.

Conclusion A set of morpho-physiological traits associated with vegetative vigour is required to ensure a good SCY in agroecological cropping systems. These results provide scientific evidence and useful knowledge for breeders and research programmes on cropping systems focused on the adaptation of cotton to climate change.

Keywords Tillage, Agroecological practices, Water status, *Gossypium hirsutum*, Ideotype, Seed cotton yield, Cover crop, CSM-CROPGRO-Cotton

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Introduction

Cotton (*Gossypium hirsutum* L.) provides employment and ensures the livelihoods of millions of rural small-holder farmers in Africa (Keller et al. 2024), and the cotton industry is a pillar of the economy in Sudano-Sahelian countries in West Africa. In Benin, the cotton industry employs 30% of the entire workforce and accounts for 53% of export earnings (Chabi Simin Najib et al. 2022).

In most West and Central African countries, cotton is grown as a rainfed crop and is consequently subjected to climatic constraints, along with delayed sowing and limited boll production (Sekloka et al. 2016). In Benin, the most common cotton production system is characterised by plough-based tillage, the use of 100 to 250 kg·ha⁻¹ of fertilizer (N, P, K), and limited crop diversification mainly based on cotton/maize rotation. Crop residues are left on the soil during the dry season and are subject to animal grazing or burning, thereby limiting benefits to the following crops. As a result, in such agroecosystems, seed cotton yield (SCY) and cereal yields are low and soil fertility declines (Amonmide et al. 2019). Despite the ongoing efforts by cotton breeders, the average SCY stagnates around 1.2 t·ha⁻¹, whereas the theoretical potential yield is 4.5 t·ha⁻¹ (Aboua et al. 2021). Until now, cotton variety breeding in Benin has been conducted in tillage cropping systems, resulting in full-season and late-maturing cultivars. These cultivars are arborescent, and their life cycle is well adapted to adequate rainfall conditions (Sekloka et al. 2008). In the context of soil degradation, soil conservation practices based on reduced or no-tillage, permanent soil cover and diversified crop rotations are recommended as an alternative to tillage-based cropping systems (Atakoun et al. 2023). Breeding cultivars is a cornerstone in many cotton cropping systems (Constable 2000), but current methods of evaluation need to be reviewed to develop agroecological cropping systems and to improve the productivity of cotton cultivars. The emerging challenge for breeders is therefore to select new cultivars adapted to innovative cropping systems by firstly exploring the existing genetic diversity (Gouleau et al. 2021).

Moreover, because of the adverse effects of climate change in Benin, cotton yield could fall significantly by up to 20% by 2050 (Akponikpe et al. 2019). Thus, the screening of genotypes adapted to new cropping systems must be carried out considering future global climate change with the expected effects produced by elevated carbon dioxide in the atmosphere, increased temperature, and enhanced rainfall variability (droughts, floods) (Iqbal et al. 2022). A single genotype cannot combine all desirable morpho-physiological traits of interest. Therefore, breeders aim to combine several favourable traits in a

single germplasm and design ideotypes for this purpose. A varietal ideotype has been defined as "an optimal combination of morphological and physiological traits for a given environment, production method and use" (Martre et al. 2015).

Crop simulation models (CSM) are powerful tools for predicting the impact of climate change, innovative crop management practices, and new traits-based breeding technologies on crop production and farming systems (Muller et al. 2019). They can also help to understand the direct effects of individual plant trait, combination of traits, or genotype (G) × environment (E) interactions on crop yield recognized as a complex quantitative trait (Boote et al. 2001). While several cotton models have been successfully used around the world, the CSM-CROPGRO-Cotton has been the most widely used particularly in Africa (Abbas et al. 2020). This model has been used to simulate the effect of conservation agriculture systems on the performance of maize in Zimbabwe (Corbeels et al. 2016), to design cotton ideotypes in Cameroon (Gérardeaux et al. 2018), and to assess the effects of climate change on cotton production in Cameroon (Gérardeaux et al. 2013) and Benin (Amouzou et al. 2018).

In Africa, particularly in Benin, to our knowledge, the genetic diversity of cotton cultivars has not been assessed or documented in agroecological cropping systems, and the CROPGRO-Cotton model has not been used to identify and evaluate the traits of interest, or to design cotton ideotypes in the context of climate change. Thus the objectives of the present study were to (i) evaluate the relative contribution of the plant traits that drive G × E × M (management) interactions to SCY as measured in field experiments, and to explain the results using the CSM-CROPGRO-Cotton embedded in the decision support system for agrotechnology transfer (DSSAT), (ii) identify morpho-physiological traits for yield enhancement in agroecological cropping systems in Benin, and (iii) identify optimum combinations of different cultivar parameters used in the CSM under current and future weather conditions.

Materials and methods

Study sites

We conducted the study from 2020 to 2023 in two experimental sites managed by the Cotton Research Institute (IRC): Soadoudou and Savalou. Both sites are in major cotton-growing regions of Benin. Soadoudou (10°29'N, 1°98'W, 425 m above sea level) is characterised by a Sudano-Sahelian climate with an average annual rainfall of (1 028 ± 162) mm recorded over the period 1970–2023, following an unimodal pattern from May to October. Savalou (7°90'N, 1°92'W, 300

m above sea level) is located in the southern part of the Sudano-Guinean climate zone, which represents a transition zone to the bimodal rainfall pattern in the south. In Savalou, two growing seasons are expected per year, one from March to mid-July, and the other from mid-August to November during which an annual average of $(1\,075 \pm 203)$ mm of rain fell in the period 1970–2023. An additional experiment was carried out in 2022 in Okpara ($9^{\circ}18'N$, $2^{\circ}41'E$, 320 m above sea level) to assess the earliness of the cotton cultivars studied. The soils at all the sites are classified as Luvisols according to the world reference database (FAO 2023). The soil depth easily reached by cotton roots was 65 cm and 80 cm in Savalou and Soaodou, respectively. The soil physical and chemical properties of the respective sites are shown in Table S1.

During the experimental period, the total annual rainfall from planting to cotton harvest in each zone ranged from 1 067 to 1 241 mm in Soaodou, and from 863 to 1 100 mm in Savalou. Average minimum and maximum temperatures were similar at the two sites over the four years of the study, with values of $22^{\circ}C$ and $32^{\circ}C$, respectively. Soaodou, in the north, received slightly more global radiation than Savalou (Table S2).

Field experiments

Two types of experiments were conducted at two sites, Savalou and Soaodou (Table S3). The first one was the main trial ($G \times E \times M$), in which five cotton cultivars were compared in four cropping systems termed plough-based tillage (PT), PT with incorporation of cover crop biomass (PTI), conservation agriculture with strip tillage (CA_ST), and conservation agriculture with no tillage (CA_NT). The experimental design was a split plot with 6 replicates (blocks). In the main 160 m² plots, the four cropping systems were randomised in a complete block design, and the cotton cultivars were then randomly assigned to 27 m² subplots. The second type of experiment was composed of several classical variety trials: (i) four trials (varietal characterisation, VC) in Savalou and Soaodou in 2022 to assess the yield potential of the five varieties under optimal growing conditions, i.e., ploughing and increased mineral fertilization; (ii) a trial (varietal earliness, VE) conducted in Okpara in 2022 to collect more data on the phenology (flowering and maturity) of the six cultivars. Both VC and VE experiments were dedicated to the empirical parameterization of the crop growth model.

Cropping systems management

Cotton-maize rotation, which is the most common cotton-based cropping system in Benin, was used in our study. In 2020 and 2022, maize was planted

as a sole crop or combined with one or two cover crops, depending on the cropping system. Cotton was planted as the sole crop in 2021 and 2023 (Fig. S1). The four cropping systems in comparison were characterised by the intensity of tillage, crop diversification and management of the crop residues. PT soil management differed at the two sites. In Soaodou, a region where crops and livestock are closely associated, crop residues are generally grazed by cows and sheep at the end of the rainy season. This practice was simulated in the experiment by manually exporting crop residues from the plots and then applying 400 kg·hm⁻² of farmyard manure before ploughing. As cattle rearing is not widely practised in Savalou, no grazing was simulated, and crop residues were not exported. In addition, cowpea (*Vigna unguiculata* (L) Walp.) was sown directly in the first rainy season (April–June), and the residues were buried during the second rainy season from July to November. A calcium phosphate amendment (22% P₂O₅, 43% CaO, 4% S) at a dose of 300 kg·hm⁻² was introduced in the PTI system in 2020 in line with practices recommended by the cotton industry in Benin. Strip tillage of the seed rows was carried out on dry soil to a depth of 15 cm before the start of the rainy season in CA_ST. In Soaodou, partial grazing is allowed, so the study simulated it by exporting half the crop residues and applying 200 kg·hm⁻² of manure in the seed rows. To keep the soil covered with crop residues, no grazing was allowed in CA_NT. The CA_NT system consisted of no tillage, approximately 85% of the soil surface being covered with a mulch of plant litter, and the inclusion of two leguminous cover crops (*Crotalaria retusa* L. and *Stylosanthes guianensis* Aublet S.) with maize. The CA_NT system exploits the regrowth capacity of *S. guianensis* to increase the soil cover after the maize was harvested. Crops were managed in line with practices recommended by the cotton industry for weed and pest control (Table S4).

Cotton cultivars

Overall, six cotton cultivars from different origins, with different cycle lengths (e.g., early and late maturing), growth habits, leaf attributes, and seed characters, were evaluated in this study (Table S5). Four cultivars (Guazuncho2, Tamcot_camde, Oultan, and S188) were common in both sites, and two local cultivars were included as controls: Ang956 in Soaodou and Okp768 in Savalou. These tested cultivars were chosen to represent most of the diversity of morpho-physiological traits among *Gossypium hirsutum* (Narayanan et al. 2014). The crop canopy with respect to leaf shape and growth habit has received considerable attention, suggesting a potential to optimise solar radiation

interception through adjustment of planting density. Thus, a higher planting density was used for compact cultivars (Sekloka et al. 2008) and for genotypes with okra leaf morphology (Wells et al. 2010). In all cropping systems, the cultivars Ang956, Okp768, and Gua-zuncho2 were planted with 0.8 m spacing between rows and 0.3 m between holes in the row with 3 seeds per hole, subsequently thinned to one plant per hole, leading to a density of 41 666 plants·hm⁻². A planting density of 125 000 plants·hm⁻² was aimed for the cultivars Tamcot_camde, Oultan, and S188 (0.4 m between-row spacing, 0.2 m within-row spacing, with one plant per hole after thinning).

Data collection

Soil characterisation of cropping systems

Soil chemical analysis, focused on nitrogen content, carbon content, and pH, was performed on samples collected from the 0–10, 10–20, and 20–40 cm soil layers in June 2021 and June 2023 to assess the soil fertility of the cropping systems before the cotton varieties were planted.

Soil moisture in the cropping systems was assessed by sampling soil cores at depths of 0–20, 20–40, and 40–60 cm in 2021 and 2023 during the cotton cycle [(15, 30, 45, 60, 75, 90, 105, 120, 135, 150 days after planting (DAP)]. Samples were weighed immediately after collection, and then oven-dried at 105 °C to constant weight to estimate soil water content. Soil moisture at field capacity was determined by measuring water content after heavy rainfall (> 40 mm) in September, the wettest month. Soil moisture at the wilting point was measured in December, i.e., at the start of the dry season. The soil extractable water, evaluated in each 0–20 cm topsoil and at the rooting depth, was calculated according to Ridremont et al. (2011) as:

$$EW(\text{profile}) = \sum_{i=1}^n EW[(\text{layer})i] \quad (1)$$

$$EW(\text{layer}) = (M_{fc} - M_{wp}) \times BD \times D_p \times (1 - SF) \quad (2)$$

where, (layer)*i* is the depth of layer *i*, *EW* is extractable water (mm); *M_{fc}* and *M_{wp}* are the moisture contents at field capacity and at wilting point (g·hg⁻¹), respectively; *BD* is the bulk density (g·cm⁻³) of the topsoil; *D_p* is the depth of the layer (dm); and *SF* is the percentage of stone fragments.

Growth and development of cotton cultivars

• Phenology

The dates of anthesis and physiological maturity were noted when half of the plants in the rows of a given experimental plot had produced their first flower or the first boll had opened, respectively.

• Morpho-physiological indexes measurement

To determine the contribution of different morpho-physiological parameters to seed yield, the leaf area index (LAI) and leaf chlorophyll content were assessed in 2021 and 2023, completed by specific leaf area (SLA) in 2023. LAI was measured using the LI-COR LAI-2200C Plant Canopy Analyzer (Li-COR Inc., Lincoln, NE, USA) for five times during the cotton cycle (30, 45, 60, 90, 120 DAP). To assess the nitrogen nutrition status of the cotton plants, leaf chlorophyll content was measured with a portable soil and plant analysis development (SPAD) chlorophyll meter SPAD-502 (Minolta, Tokyo, Japan). Three SPAD measurements were made on the third, fourth, and fifth most recent, fully expanded leaves, appearing on the main stem counting from the top (Yang et al. 2016). These measurements were taken on five consecutive plants in each subplot. The seed oil content was determined for each cultivar in the seed analysis laboratory of the Benin Oil Company. To measure SLA, a sample comprising 6 to 8 plants was taken from an unharvested row at 60 DAP. Two discs, 1.2 cm and 5 cm in diameter, were used to cut out all the leaves on the sampled plants. The cut leaves were then oven-dried at 105 °C to constant weight and SLA was calculated as follows:

$$SLA \left(\text{cm}^2 \cdot \text{g}^{-1} \right) = \frac{\text{Surface of cut leaves (cm}^2\text{)}}{\text{Dry mass of cut leaves (g)}} \quad (3)$$

• Biomass, SCY, and yield components

The biomass of the cotton cultivars was assessed on plants sampled in a 1.5 m unharvested row at 90 DAP in 2021 and at 60 and 90 DAP in 2023. Aboveground vegetative and reproductive organs, and root tissues were separated and dried to obtain dry biomass. Before the roots were dried, the length of the pivot, the number and length of secondary roots were measured on each plant (Djoulet et al. 1994). Three 4.2 m planting rows were used for low-density cultivars, and six rows for

high-density cultivars, i.e., the same area of 10.08 m² was used for harvesting. At harvest, the height and length of the 3rd (usually the longest) fruiting branch of five consecutive plants in each plot were measured. The number of plants and bolls harvested was counted and expressed as numbers per m². The average cotton boll weight was calculated by dividing the weight of seed cotton by the number of bolls harvested. Before harvest, 50 bolls with carpels were sampled from each plot and weighed with and without carpels to determine the ratio of seed cotton weight to boll weight. Subsequently, the weight of a seed covered in fibre was determined by dividing the weight of seed cotton inside the 50 bolls sampled by the number of seeds.

Crop modelling to design ideotypes

Cropping system model

The CSM-CROPGRO-Cotton of DSSAT simulates the growth, development, and yield of cotton in response to soil water, weather conditions, nitrogen availability, and soil management practices (Jones et al. 2011; Mishra et al. 2021). The ability of CSM to simulate effects of tillage and surface crop residues increases the potential applications of the model, especially in relation to soil water, nutrients, and soil organic matter management (White et al. 2010). Thus, DSSAT has been increasingly used as a tool to compare the performance of different cropping systems and crop production technologies in a wide range of environments (Caviglia et al. 2013), especially for maize under conservation agriculture in Zimbabwe (Corbeels et al. 2016). The version 4.8.2 of DSSAT was used in our study (Hoogenboom et al. 2021).

Calibration and evaluation data sets

In the first step of calibration, soil hydrological properties were derived from soil texture in 2020, and water dynamics were monitored in 2021 (Fig. S2) (Ale et al. 2021). The following soil properties were calculated and fitted from the observed data: field capacity (drained upper limit, DUL), permanent wilting point (lower limit, LL), saturated soil water content (SSAT), saturated hydraulic conductivity (SSKS), drainage coefficient (SLDR), run-off curve number (SLRO), and soil root growth factor (SRGF).

The second step was to calibrate coefficients of genetic parameters to represent cotton cultivars. Calibration was carried out using the best-yielding cropping systems PT and PTI in 2021, and VE and VC trials in 2022. The methodology described by Gérardaux et al. (2013) was used: phenology was calibrated first, followed by LAI, biomass, and then SCY. For calibration, we used a combination of tools, generalised likelihood uncertainty analysis (GLUE) and GEN SELECT, and finally a manual

iterative approach by readjusting the observed data to minimise the relative root mean square error (RRMSE, %). Model simulations were evaluated using the observed data (water dynamics, phenology, biomass, and SCY) of the cropping systems CA_ST and CA_NT of the G × E × M experiment in 2021, and all 2023 data that had not been used for calibration.

During model calibration and evaluation, different statistical criteria, namely the coefficient of determination (R^2), root mean square error (RMSE), relative RMSE (RRMSE), and index of agreement (d) of the observed and simulated values were computed to assess the prediction accuracy (Table S6). Calibration was complete when the last step, SCY was adequately simulated and RRMSE was below 20%, and R^2 was above 0.75.

Statistical analysis

Data processing, statistical analysis and graphics using the *ggplot2* package were performed with R software version 4.4.1 (R Core Team 2024) to test the effects of cropping systems, cultivars, and their interactions and to identify the best ones for each site based on SCY. The data were analysed using linear mixed effect models and the *lme4* package to estimate effect sizes. The *lmerTest* was used to test hypotheses (Kuznetsova et al. 2017). In this analysis, the cropping system and cultivar were considered fixed, while the block, plot and subplot factors were considered random according to the mixed model. When fixed effects were significant ($P < 0.05$), the *emmeans* package with default parameters was used to calculate multiple comparisons of fixed factor levels with the Tukey's honest significant difference (HSD) test (Lenth 2023).

Method used to design ideotypes

Testing all the possible ideotypes with the combinations of 18 genetic traits (Table S7) would mean testing millions of cultivars. We conducted a sensitivity analysis to select the five most sensitive genetic traits, which were associated with the best yielding cultivars Tamcot_camde and Okp768. We identified the following traits: (i) time between the appearance of the first flower and the end of leaf expansion [$+$ (FL-LF)], (ii) maximum leaf photosynthesis rate ($\pm$ LFMAX), (iii) specific leaf area under standard conditions ($\pm$ SLAVR), (iv) maximum size of full leaf ($+$ SIZLF), (v) maximum weight per seed ($+$ WTPSD), and (vi) ecotype relative height compared with standard height per node ($\pm$ RHGHT). The sign " $+$ " means positively, while " $-$ " means negatively correlated with the yield. To reproduce the growth strategies of known crops in terms of leaf area dynamics and photosynthesis (Wright et al. 2004), we respected a negative correlation

between the thinness of leaves and their photosynthetic capacity. Thus, we reduced the genetic trait SLAVR value when we increased the LFMAX. The starting cultivars were Okp768 in Savalou and Tamco_camde in Soaodou. Next, we generated virtual cultivars by changing the coefficients of 1, 2, 3, 4, or 5 of the genetic traits by 5% and 10% and ran all 30 possible combinations (Table S8). The 30 ideotypes for each location were simulated, and SCY were compared with the original cultivar and the control cultivar grown in the study region.

Climate change scenarios and performance of the ideotypes

To assess the performance of the ideotypes, long-term simulations were run using historical daily climate data (rainfall, maximum and minimum temperatures, solar radiation) from 2003 to 2023 collected by the Benin Meteorological Agency's synoptic stations located nearest to our experimental sites. Future climate scenarios were estimated through the Representative Concentration Pathways (RCP) based greenhouse gas (GHG) concentration trajectories from the Intergovernmental Panel on Climate Change (IPCC 2014). Three RCP (RCP 2.6, 4.5, and 8.5) were used to predict CO₂ concentrations of 400, 500, and 600 $\mu\text{L}\cdot\text{L}^{-1}$, respectively, by 2050. Climate change predictions suggest significant inter-annual variability in simulated precipitation by 2050 in Benin, with the number of years with rainfall deficits predicted to increase in the future (Akponikpe et al. 2019). Climate models predict a decrease in solar radiation of 0.4, 0.3, and 0.5 $\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for RCP 2.6, RCP 4.5, and RCP 8.5, respectively, and precipitation variability of -2%, -4%, and +1% for the three RCP scenarios. These RCP scenarios showed increasing trends in both minimum temperature (1.0, 2.0, 4.7 °C) and maximum temperature (1.1, 2.0, 4.6 °C) (Amouzou et al. 2018). We simulated water use efficiency (WUE) and nitrogen use efficiency (NUE), following the methods of Amouzou et al. (2018). WUE is expressed as SCY per unit of evapotranspiration ($\text{kg}\cdot\text{mm}^{-1}$), and NUE by SCY per N uptake ($\text{kg}\cdot\text{kg}^{-1}$).

Results

Model calibration

Soil parameters and water dynamics in the cropping systems

DUL, LL, and SSAT differed between the two sites. SSKS was similar in the top horizons but differed in deeper ones, being lower at greater depth in Soaodou. The drainage rate was better in Savalou than in Soaodou, enabling us to adjust SLDR to 0.5 and 0.3, respectively, and SLRO was adjusted to 93 and 92, respectively. In terms of fertility, soil fertility factor (SLPF) of 1.00 and 0.85 was used in

Soaodou and Savalou, respectively, suggesting better soil fertility in Soaodou (Table S9, S10).

The cropping system SRGF, which we used, took into consideration the physical constraints observed in CA_ST and CA_NT systems. Thus, we assigned lower coefficients to these systems from a depth of 0.20 m downwards. Observations showed that root growth in deeper layers was impaired in CA systems. The taproot in CA_NT was significantly shorter than that in PTI and PT in Savalou and in PTI in Soaodou. However, the length of secondary roots was not significantly different among CA_NT, PT, and PTI in Savalou. In Soaodou, there was better growth of secondary roots in terms of number and length in CA_NT than in PT and PTI. Root biomass was the highest in PTI in Savalou, while it was not significantly different in all cropping systems in Soaodou (Fig. S3).

The model satisfactorily simulated the observed extractable water dynamics in the soil profile in the rainfed cropping systems used for calibration ($d \geq 0.80$) with RRMSE ranging from 25% to 40% (Fig. 1).

Genetic traits of the cotton cultivars calibrated with CROPGRO-Cotton

Model calibration was used to estimate the coefficients of the genetic traits of the six cultivars (Table S7). CROPGRO-Cotton simulated the phenology of six cultivars adequately predicting the observed anthesis and physiological maturity with a maximum RMSE of 3.5 days and 2.0 days, respectively (Table 1).

Overall, the model satisfactorily simulated the maximum leaf area index (LAI max) of the Ang956, Okp768, and Guazuncho2 varieties, with estimated values ranging from 3.3 to 3.8, and RMSE comprised between 0.1 and 0.5. The model overestimated the LAI max of Oultan, S188, and Tamcot-camde varieties (from 4.2 to 4.8) sown at higher densities, with RMSE ranging from 0.9 to 1.4. Canopy height was correctly calibrated with RMSE ranging from 0.1 m to 0.5 m (Table 1).

The CROPGRO-Cotton model also satisfactorily simulated the SCY of cultivars ranging from 1 398 $\text{kg}\cdot\text{ha}^{-1}$ (Oultan) to 2 348 $\text{kg}\cdot\text{ha}^{-1}$ (Ang956) with d ranging from 0.75 to 0.88 (Table 1).

Model evaluation

Water dynamics in the cropping systems

Evaluation of extractable water dynamics in the soil profile under rainfed cropping systems showed that the degree of agreement between simulations and observations was also good (d ranging from 0.86 to 0.97) with RRMSE ranging from 15% to 27% (Fig. 2). However, the model slightly underestimated soil moisture from 60

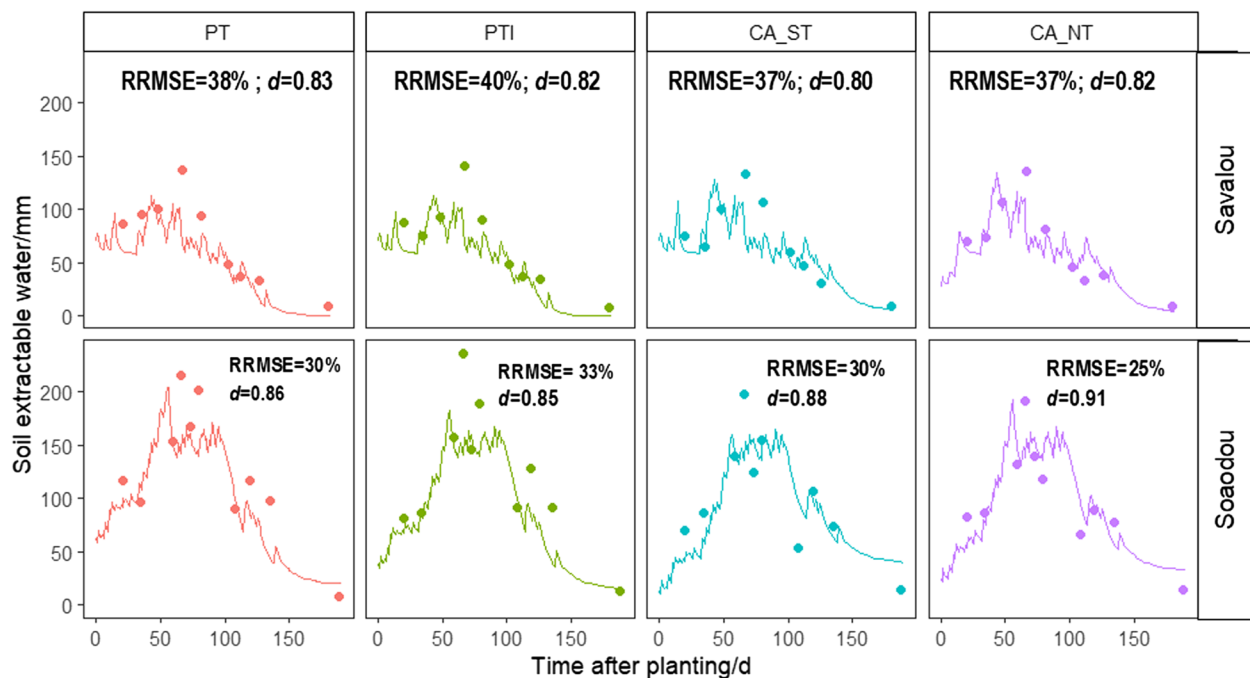


Fig. 1 Measured and simulated soil extractable water over rooting depth in the different cropping systems used for calibration. Quadrilaterals represent observed data; curves represent simulated data

to 105 DAP in PT in Savalou, and in PTI and CA_ST in Soaodou. Overall, model evaluation performed well and could be used to assess soil water dynamics in agroecological cropping systems in both sites.

Growth and development of cotton cultivars

The model was satisfactorily evaluated using a graphical comparison of the mean values of the measured and simulated phenological stages. This confirmed the earliness (Oultan, Tamcot_camde), lateness (S188, Okp768, Ang956), and moderately lateness maturity (Guazuncho2) of the cultivars (Fig. 3A, B).

Simulation accuracy of LAI during model evaluation was satisfactory for all varieties and cropping systems with good R^2 values (0.83 in Savalou, and 0.80 in Soaodou). However, the model tended to overestimate LAI in Soaodou (Fig. 3C, D).

There was a close agreement between the observed and simulated SCY for the cropping systems and cultivars studied, with high R^2 values (0.81 in Savalou, and 0.78 in Soaodou). The degree of agreement of the model simulation was also good ($d > 0.90$). For the combined two years of cotton cultivation (2021 and 2023), difference in cropping systems performance was observed

between sites based on observed SCY. PTI cropping system was the best in Savalou ($2\,832\text{ kg}\cdot\text{ha}^{-1}$) (Fig. 3E), while higher average observed SCYs were obtained in CA_ST ($2\,183\text{ kg}\cdot\text{ha}^{-1}$) and CA_NT ($2\,129\text{ kg}\cdot\text{ha}^{-1}$) cropping systems in Soaodou (Fig. 3F).

There was no significant interaction between genotypes and cropping systems in Savalou, and the control cultivar Okp768 performed better in PTI ($3\,083\text{ kg}\cdot\text{ha}^{-1}$) in 2023. In Soaodou, a significant interaction between cultivars and cropping systems was observed, with Tamcot_camde performing best in CA_ST ($3\,304\text{ kg}\cdot\text{ha}^{-1}$) and CA_NT ($2\,958\text{ kg}\cdot\text{ha}^{-1}$) in 2023.

Okp768 significantly performed better in PTI than in CA_ST and CA_NT in Savalou. Tamcot_camde performed better in CA_NT and CA_ST cropping systems in Soaodou. These cultivars share similar coefficients for these genetic traits: FL-LF, LFMAX, SLAVR, SIZLF, WTPSD, and RHGHT (Table S7). Interpretation of these coefficients revealed that the larger seeds, wider and thicker leaves, longer mature period, and lower or higher height of these cultivars are favourable traits to obtain increased SCY in agroecological cropping systems. Thick leaves improve the photosynthetic capacity of these cultivars.

Table 1 Comparison between the observed and simulated data in the calibration data set

Cultivar	Item	Phenology		Morphology		Biomass and yield			
		Anthesis time/d	Maturity time/d	LAI max	Canopy height/m	Aboveground biomass/(kg·ha ⁻¹)	Number of seeds at maturity/(m ⁻²)	Seed cotton yield/(kg·ha ⁻¹)	Max ratio of seed cotton mass to boll mass/%
Ang956	Obs	62	115	3.4	1.3	5 931	1 398	1 939	71.4
	Sim	62	114	3.8	1.2	6 235	1 310	2 348	71.5
	n.obs	5	5	3	3	3	3	3	3
	RMSE	3.5	0.9	0.5	0.1	-	171	314	0.6
	d	0.58	0.97	0.71	0.76	-	0.85	0.81	0.75
Okp768	Obs	62	113	3.1	1.0	4 057	864	1 649	73.7
	Sim	62	113	3.6	1.1	5 903	1 169	1 586	74.3
	n.obs	5	4	3	3	3	3	3	3
	RMSE	2.6	1.2	0.1	0.5	-	320	255	1.2
	d	0.57	0.97	0.80	0.89	-	0.60	0.75	0.60
Guazuncho2	Obs	60	111	3.5	1.0	6 355	1 390	1 894	70.5
	Sim	60	111	3.3	1.0	5 929	1 166	1 980	70.1
	n.obs	9	8	6	6	6	6	6	6
	RMSE	2.8	1.9	0.5	0.1	-	381	505	1.4
	d	0.55	0.93	0.87	0.74	-	0.83	0.80	0.72
Oultan	Obs	58	110	3.8	1.0	6 007	982	1 515	70.2
	Sim	58	110	4.6	1.1	6 336	856	1 398	70.8
	n.obs	9	8	6	6	6	6	6	6
	RMSE	3.0	1.8	1.3	0.1	-	482	578	1.1
	d	0.47	0.93	0.77	0.59	-	0.67	0.86	0.72
S188	Obs	63	116	3.9	1.0	5 982	1 280	1 991	71.4
	Sim	63	115	4.2	1.0	6 837	990	1 763	71.7
	n.obs	9	8	6	6	6	6	6	6
	RMSE	3.3	1.1	1.4	0.1	-	523	608	2.2
	d	0.45	0.97	0.73	0.82	-	0.63	0.86	0.65
Tamcot_camde	Obs	59	110	4	0.8	5 437	1 311	2 008	72
	Sim	59	110	4.8	0.8	6 502	1 160	1 919	71.8
	n.obs	9	8	6	6	6	6	6	6
	RMSE	3.4	2.0	0.9	0.1	-	550	384	1.4
	d	0.43	0.92	0.77	0.87	-	0.53	0.88	0.50

max maximum, Obs observation, Sim simulation, n.obs number of observations, RMSE root mean square error, d index of agreement. "-" indicates no such item

Long-term simulation of SCY in agroecological cropping systems

Of the 30 virtual cultivars generated at each site, the ideotypes (i) Okp768_ideo21 combining a 10% increase in LFMAX, SIZFL, WTPSD, and a 10% decrease in SLAVR, and (ii) Okp768_ideo29 with all the characteristics of Okp768-ideo21 plus a 10% increase in FL-LF proved to be superior in Savalou. CROPGRO-Cotton model simulations from 2003 to 2023 showed a 4.1% SCY improvement for PTI compared with PT control for all Okp768 and ideotypes. The ideotypes Okp768_ideo21 and Okp768_ideo29 in cropping system PT would result in

a 2.5% and 2.4% increase in SCY, respectively, compared with the control Okp768. In PTI, the increase in SCY for the ideotypes Okp768_ideo21 and Okp_ideo29 would be 3.7% and 3.1%, respectively, compared with Okp768 (Fig. 4A). Yield increases due to cropping systems and ideotypes are comparable and additive.

In Soadoudou, Tamcot_camde_ideo30 ideotype combining a 10% increase in LFMAX, SIZFL, WTSPD, FL-LF, and a 10% decrease in SLAVR and RHGHT proved to be the best. Simulations with historical data from 2003 to 2023 showed an average increase in SCY of 207% in CA_NT compared with the PT control. The

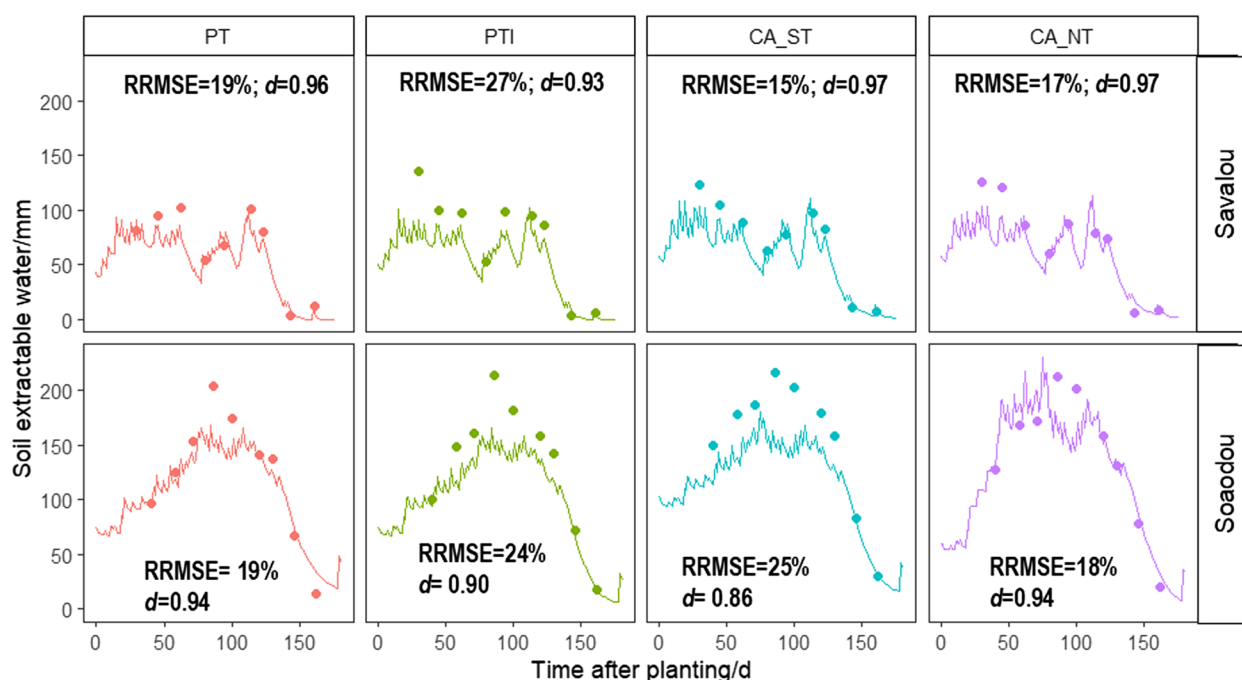


Fig. 2 Measured and simulated soil extractable water over rooting depth in the different cropping systems used for evaluation. Quadrilaterals represent observed data; curves represent simulated data

SCY of Tamcot_camde and Tamcot_camde_ideo30 would be reduced by 11% and 13%, respectively, compared with the control Ang956 in PT; while it would be increased by 1.5% and 4.2% in CA_NT, respectively (Fig. 4B). The increase in yield is mainly due to the change in cropping system.

Impacts of climate change on cotton production

Variation of SCY

SCY of the ideotypes varied under the assumed future climate scenarios in Savalou (Table 2). The ideotypes Okp768_ideo21 and Okp768_ideo29 would perform well under all RCP but would have best SCY under the future RCP 8.5 scenario with the increase of 3.1%–3.2% compared with the control. In Soaodou, Tamcot_camde_ideo30 and Tamcot_camde would perform well under all RCP. Compared with Ang956, the SCY of Tamcot_camde and Tamcot_camde_ideo30 increased by 172% and 167%, respectively under RCP 4.5.

Changes in water and nitrogen use efficiencies

For Okp768_ideo21 and Okp768_ideo29 in Savalou, the model predicted the same increase in WUE: 5.6% for RCP 2.6, and 3.2% for RCP 8.5, respectively. Only WUE of Okp768_ideo29 would increase by 1.6% for RCP 4.5.

For NUE, the same increase of 10.1%, 13.2%, 14.2% was predicted for the 2 ideotypes under RCP 2.6, RCP 4.5, and RCP 8.5, respectively (Table 2).

The increase in WUE and NUE is more pronounced for Tamcot_camde_ideo30 and Tamcot_camde in Soaodou under future climate scenarios. The magnitude of resource use efficiency improvement reached 248%–259%, 231%–238%, and 200%–206% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively, for WUE; and 234%–239%, 221%–226% and 181%–185%, respectively, for NUE. The ideotype Tamcot_camde_ideo30 is higher water efficient and less nitrogen efficient than Tamcot_camde cultivar (Table 2).

Discussion

Morpho-physiological traits of cotton cultivars adapted to agroecological cropping systems

Early vigour is a necessary characteristic for seedling emergence and development in less frequently tilled soils covered with crop residues (Adams et al. 2020). It is linked to the large size of seeds, which produce seedlings with larger root systems (Virk et al. 2019; Snider et al. 2022). Both reduced till and no till systems lead to smaller roots, thickening of roots, greater lateral branching (McMichael et al. 2010), and have a negative impact

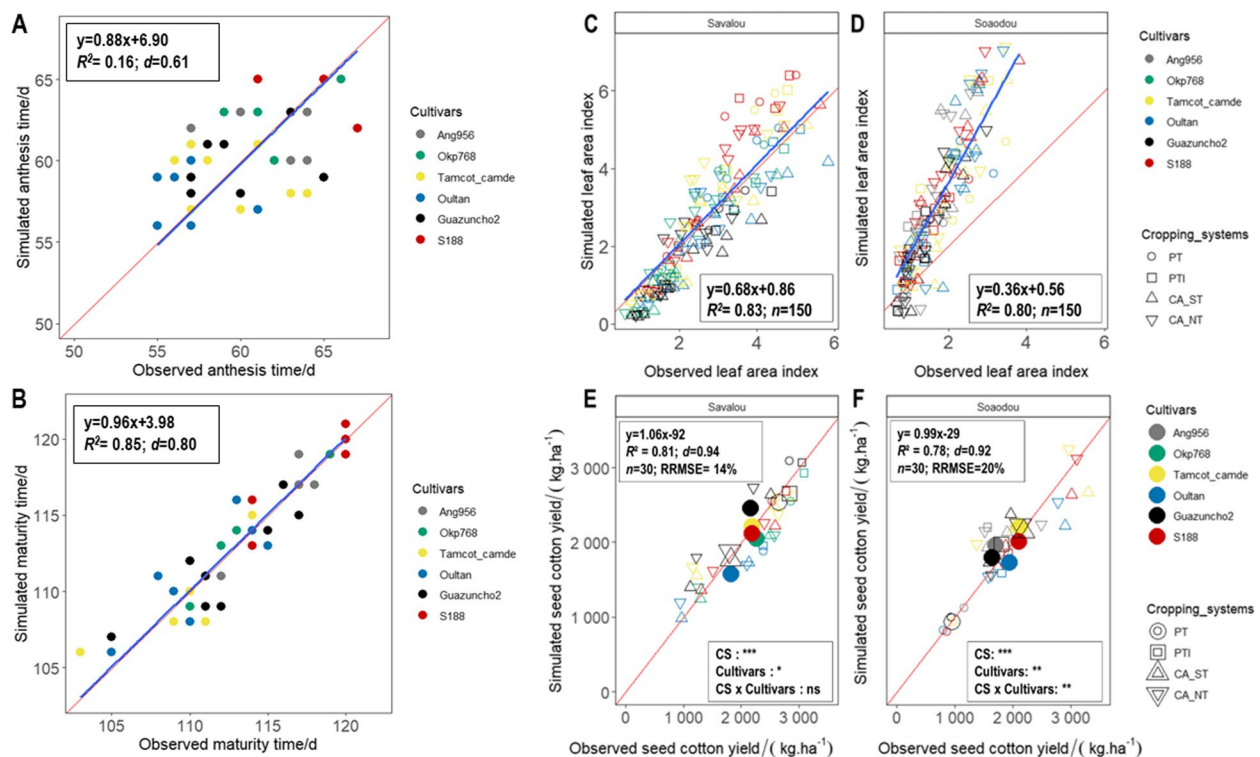


Fig. 3 Observed and simulated growth and development parameters of cotton cultivars under model evaluation. **A, B** Phenology. Observed and simulated anthesis time (**A**) and maturity time (**B**) of cotton cultivars under model evaluation. **C, D** Leaf area index. Observed and simulated leaf area index for cotton cultivars and cropping systems under model evaluation in Savalou (**C**) and Soaodou (**D**). Colours represent cultivars, shapes in black represent cropping systems; shapes in other colours represent cropping system and cultivar combinations. **E, F** Seed cotton yield. Observed and simulated seed cotton yield for cotton cultivars as a function of cropping systems under model evaluation in Savalou (**E**) and Soaodou (**F**). Colours represent cultivars, shapes in black represent cropping systems; Large shapes in black represent the average yield of each cropping system; Small shapes in other colours represent average yields for combinations of cropping system and cultivars. The large dots represent the average yield of each cultivar. CS: cropping system; x: interaction. ***, significant at $P < 0.001$; **, significant at $P < 0.01$; *, significant at $P < 0.05$; ns: non-significant

on photosynthetic activity, thus contributing to more rapid leaf senescence, particularly in cereals (Janusau-skaite et al. 2022). Physical restriction of cotton root growth results in more compact plants, earlier maturity and a higher harvest index (Carmi et al. 1983; Gwathmey et al. 2010). Under these conditions, cotton cultivars with the ability to produce more lateral root branches and leaves with higher photosynthetic activity are required. The increased production of lateral roots could lead to an improvement in the plant water status (McMichael et al. 1985). These lateral roots could also exploit a greater volume of the first soil horizons, which are richer in nutrients under conservation agriculture. The morpho-physiological characteristics of Tamcot_camde, including increased seedling vigour, early formation of true leaves and more lateral roots (Reddy et al. 1988), could explain its adaptation to the conservation agriculture systems.

In addition, the relatively short height of Tamcot_camde became an advantage in conservation agriculture because it avoided plant lodging caused by large boll production per plant. Indeed, in Benin, ridging is usually carried out by 40 DAP in PT, the soil being placed around the plant collars to prevent lodging.

LFMAX is related to the characteristics that maintain high photosynthesis (Boote et al. 2001) and associated with plants with thick leaves (Pettigrew et al. 1993). This trait is positively correlated with yield (Wells et al. 1986). Indeed, the leaves contain more chlorophyll and consequently high nitrogen concentrations (Iqbal et al. 2020). These leaves are known to have lower SLA values. Tamcot_camde and Okp768 exhibited low values of SLA, which maintains the plant's photosynthetic activity for longer and delays leaf senescence. This trait known as "stay green" maintains the green colour of the stem and leaf during physiological maturity and plays an important

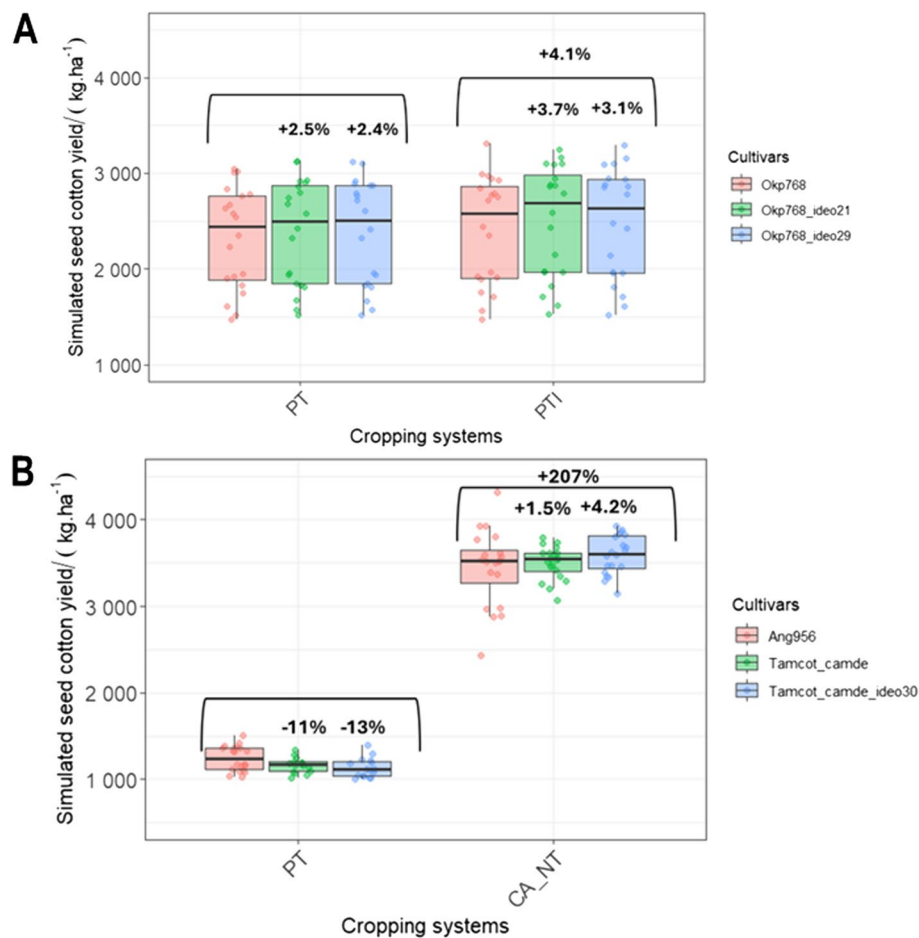


Fig. 4 Simulated seed cotton yield of ideotypes and the control in cropping systems using historical weather data from 2003 to 2023 in Savalou (A) and Soaodou (B)

role in the increase of grain size in wheat (Silva et al. 2001), maize (Chibane et al. 2021), and cotton (Yan et al. 2004).

Impact of climate change scenarios on ideotype performance

The CROPGRO-Cotton model predicted a large increase in SCY for Okp768_ideo21 under RCP 8.5 and for Tamcot_camde under RCP 4.5 in the selected agroecological cropping systems. The ideotype traits of late maturity and long boll-filling duration agree with the results of Kothari et al. (2021), whose research was conducted in Texas High Plains under dry production conditions like those in Benin. An 11%–45% increase of SCY was predicted under future climate change by 2036–2065 in Texas. Our results revealed better use of water and nitrogen by the ideotypes under the different climate change scenarios in PTI and CA_NT cropping systems

in central and northern Benin, respectively. The performance of ideotypes under RCP 4.5 and 8.5 is therefore the result of the combined effect of increased air temperature and CO₂, WUE, and NUE. This underlines the positive effect of CO₂ on SCY revealed by Gérardaux et al. (2013) in Cameroon, Adhikari et al. (2016) in Texas High Plains, USA, and Li et al. (2024) in China. WUE and NUE increased mainly because of increased canopy photosynthesis (Reddy et al. 1995; Iqbal et al. 2020). This process appears to be well reproduced by the model, allowing us to conclude that the physiological traits of the ideotypes are compatible with climate change scenarios (RCP 4.5 and RCP 8.5). These CROPGRO-Cotton simulation results confirm the findings of Amouzou et al. (2018) concerning the need to ensure efficient and sustainable use of water and nitrogen for cotton in the expected future in West Africa.

Table 2 Simulated changes in SCY, WUE, and NUE for ideotypes in Savalou and Soaodou by 2050

Site	Climate change scenario	Cultivar	SCY/(kg·ha ⁻¹)	MC for SCY/%	WUE/(kg·mm ⁻¹)	MC for WUE/%	NUE/(kg·kg ⁻¹)	MC for NUE/%
Savalou	RCP 2.6	Okp768	2 076	-	5.4	-	238	-
		Okp768_ideo21	2 199	+ 5.9	5.7	+ 5.6	262	+ 10.1
		Okp768_ideo29	2 199	+ 5.9	5.7	+ 5.6	262	+ 10.1
	RCP 4.5	Okp768	2 392	-	6.4	-	257	-
		Okp768_ideo21	2 407	+ 0.6	6.4	0	291	+ 13.2
		Okp768_ideo29	2 416	+ 1.0	6.5	+ 1.6	291	+ 13.2
	RCP 8.5	Okp768	2 375	-	6.3	-	254	-
		Okp768_ideo21	2 453	+ 3.3	6.5	+ 3.2	290	+ 14.2
		Okp768_ideo29	2 449	+ 3.1	6.5	+ 3.2	290	+ 14.2
Soaodou	RCP 2.6	Ang956	1 204	-	2.9	-	74	-
		Tamcot_camde	2 942	+ 144	10.1	+ 248	251	+ 239
		Tamcot_camde_ideo30	3 182	+ 164	10.4	+ 259	247	+ 234
	RCP 4.5	Ang956	1 179	-	3.2	-	81	-
		Tamcot_camde	3 203	+ 172	10.6	+ 231	264	+ 226
		Tamcot_camde_ideo30	3 146	+ 167	10.8	+ 238	260	+ 221
	RCP 8.5	Ang956	1 318	-	3.5	-	93	-
		Tamcot_camde	3 162	+ 140	10.5	+ 200	265	+ 185
		Tamcot_camde_ideo30	2 748	+ 109	10.7	+ 206	261	+ 181

SCY seed cotton yield, MC Magnitude of change, WUE Water use efficiency, NUE Nitrogen use efficiency; "-" indicates no such item

Conclusion

Agroecological cropping systems can substantially improve SCY. This improvement is related to soil management practices adapted to the soil and climate conditions of the growing areas and particularly to the type of cultivar. The morpho-physiological traits and growth dynamics of cultivars identified that Tamcot_camde and Okp768 growth better match the water and nitrogen availabilities of the soil. These traits ensure improved water and nitrogen use efficiencies, and the ideotypes identified could perform well in the context of climate change. It is therefore important that Benin's cotton variety creation and breeding programmes take these factors into account to ensure the sustainability of cotton production.

Abbreviations

BD	Bulk density
CA_NT	Conservation agriculture with no tillage
CA_ST	Conservation agriculture with strip tillage
CSM	Crop simulation model
<i>d</i>	Index of agreement
DAP	Days after planting
DSSAT	Decision support system for agrotechnology transfer
DUL	Drained upper limit
EW	Extractable water
FL-LF	Time between the appearance of the first flower and the end of leaf expansion
G × E × M	Genotype × environment × management
LAI	Leaf area index

LFMAX	Maximum leaf photosynthesis rate
LL	Lower limit
NUE	Nitrogen use efficiency
PT	Plough-based tillage
PTI	Plough-based tillage with incorporation of cover crop biomass
RCP	Representative concentration pathways
RHGHT	Ecotype relative height compared with standard height per node
RMSE	Root mean square error
RRMSE	Relative root mean square error
SCY	Seed cotton yield
SIZLF	Maximum size of full leaf
SLA	Specific leaf area
SLAVR	Specific leaf area under standard conditions
SLDR	Drainage coefficient
SLPF	Soil fertility factor
SLRO	Runoff curve number
SPAD	Soil and plant analysis development
SRGF	Soil root growth factor
SSAT	Saturated soil water content
SSKS	Saturated hydraulic conductivity
VC	Varietal characterisation
VE	Varietal earliness
WTPSD	Maximum weight per seed
WUE	Water use efficiency

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42397-025-00224-2>.

Supplementary Material 1. Fig. S1 Land use, crop rotation in four cotton-based cropping systems in the 4 years experimental period. Fig. S2 Model calibration and evaluation using CROPGRO-COTTON. Fig. S3 Results of root measurements at 90 DAP in the different cropping systems.

Supplementary Material 2. Table S1 Soil physical and chemical properties at the two experimental sites in 2020. Table S2 Climate conditions at the 3 experimental sites during the study period. Table S3 Experiments conducted during the study. Table S4 Crop management. Table S5 Name, geographical origin and traits of the cultivars used in the study (Bird 1979; Reddy et al. 1988; Sekloka et al. 2008; Hougny et al. 2016). Table S6 Statistical indicators used to compute model performance (Langensiepen et al. 2008; Willmot 1981; Yang et al. 2014). Table S7 Coefficients of the genetic traits of the cotton cultivars calibrated and evaluated with CROPGRO-Cotton (Constable and Oosterhuis 2010). Table S8 Combinations of genetic traits to design ideotypes. Table S9 Soil parameters and characteristics used as inputs for cropping systems in Savalou in 2023. Table S10 Soil parameters and characteristics used as inputs for cropping systems in Soaodou in 2023.

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Authors' contributions

All the authors conceived and designed the experiments; Aboua DC, Boulakia S, Gérardeaux E, and Debaeke P performed the experiments; Aboua DC, Boulakia S, Gérardeaux E, Debaeke P, and Sekloka E analyzed the data and wrote the manuscript; all authors edited and revised the manuscript. All authors read and approved of the final manuscript.

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Data availability

All relevant data are included in the article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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