Simulating the Capacity of Rainfed Food Crop Species to Meet Social Demands in Sudanian Savanna Agro-Ecologies

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Abstract: West African land use systems have been experiencing one of the fastest transformations in the world over recent decades. The Sudanian savanna is an interesting example, as it hosts the cultivation of some crops typical of the Guinean savanna as well as some of the Sahel. Therefore, this region is likely to experience further changes in its crop portfolio over the next decades due to crop migration processes responding to environmental change. Simulation approaches can guide the development of agricultural production strategies that contribute to sustainably optimize both food and fuel production. This study used crop models already available in the APSIM platform to simulate plant production and the soil water and nutrient cycles of plots cultivated with groundnut, millet, sorghum, maize, and rice on three (two upland and one lowland) soil fertility classes and subjected to five levels of management (conventional tillage without residue incorporated to the soil and no fertilizer application; conventional tillage without residue incorporated to the soil and 5 kg N ha⁻¹; conventional tillage with residue incorporated to the soil 20 kg N ha⁻¹, and no-till herbicide treated with 50 and 100 kg N ha⁻¹). Simulation outputs were contrasted against data reported in the literature and converted into nutritional, fuel and feed yields based on the qualities and uses of their different plant comparments. Groundnut yields outperformed all of the cereals across most growing conditions, nutritional and feed indicators. Maize and rice provided the highest caloric yields, with the least fertile growing conditions. Sorghum provided average to high caloric and iron yields across all of the treatments. Millet provided the highest iron yields and high fuel yields across most treatments. Some simulated treatments could not be compared against literature review data because of their absence in actual cropping systems and the lack of experimental data. Plant production was simulated with higher accuracy than the other components of the simulation. In particular, there is a need to better parameterize and validate the rice, groundnut and millet models under Sudanian savanna conditions in order to perform more accurate comparative assessments among species.

Keywords: APSIM; fuel; feed; nutritional yield; groundnut; maize; millet; rice; sorghum

1. Introduction

Many West African savanna rural regions are densely populated and, therefore, most of the primary production is provided by cultivated lands [1]. Land use systems in these regions have been experiencing rapid changes over the last decades [2] driven by internal, national and overseas demands [3,4]. These changes have involved both cropland expansion and cereal species substitution. In parallel to such land developments, global agricultural research has increasingly targeted these regions with the aim of sustainably increasing their land productivity. However, this has not been accompanied by comprehensive comparative assessments of the trade-offs incurred by concurrent crop choices.
Most studies target either one single crop species [5–7] or a few at best [8–11], usually of industrial or commercial importance, and frequently those which potentially can provide standardized goods of global agricultural value chains. Research on important regional crops, such as millet, lags behind. Meanwhile, the economies of the region show difficulties to diversify and export high value products and services on a scale enough to improve their trade balance without draining their natural capital [12–14]. In view of the stagnation of food production per capita and widespread land degradation processes [15,16], we argue that agricultural research in the region shall prioritize the sustainable satisfaction of regional food and fuel demands.

Productivity growth is a precondition for sustaining livelihood improvements [17]. However, crop substitution has not lead to such development, as the yields of the most recently adopted crops, such as maize, have not achieved the expected levels [15]. In the Sudanian savanna belt, the crop portfolio is dominated by five crops: sorghum, millet, groundnut, maize and rice. All of them are food crops and their residues are frequently used for other purposes. They differ both in their response to growing conditions and in their qualities to satisfy nutritional and fuel requirements. Therefore, a better understanding of the trade-offs incurred by the choice of crop specie under different growing conditions is indispensable to guide agricultural research and extension policies in order to optimize the capacity of these landscapes to sustainably satisfy regional demands.

The potential levels of nutritional demands satisfaction are better indicated by means of nutritional yields [18], rather than by grain yields alone, and the satisfaction of fuel demands, in a region where biomass is the main source of fuel, by means of the quantities of harvested crop residue and their lower heating values [19]. However, these assessments are based on official statistics data, which is spatially aggregated at the level of administrative units and do not inform on the technologies and intensity of crop management in the field. Frequently, crops with a higher response to management will receive the higher amount of inputs and the highest attention by farmers, influencing the interpretation of such data in relation to the relative performance of each crop by disregarding the costs of attaining such yields.

In this regard, simulation of plant production with process-based crop models offers a great opportunity to estimate agricultural productivities. These models simulate plant growth and, therefore, the amount of biomass produced by each part of the plant, allowing an assessment of its potential food, feed and fuel provision, while simulating the exchanges of water and nutrients within the plant-soil system. Hence, these tools can also be used to estimate expected future productivities and, hence, compare the changes in the crop-species’ comparative performance under expected or advocated intensification scenarios, as well as the environmental impacts of agricultural production [20]. Given the growing body of available phenological, managerial and soil data of the Sudanian savanna belt, simulation models can be used as low cost tools to gain insights of the trade-offs between nutritional and fuel yields incurred by alternative crop species’ choices.

In this study we use APSIM, one of the worldwide leading software frameworks for agricultural systems modeling and simulation. The APSIM platform has been tested in tropical and sub-tropical semi-arid environments, showing a good ability to simulate long-term dynamics of cropping systems, hence making it suitable to gain a better understanding of the sustainability of cropland management [21,22]. APSIM growth models of millet, sorghum and maize have shown a strong correlation to observations in West African savanna agro-ecologies [23–26], while growth models of groundnut and rainfed rice have shown strong fit to observations in other semi-arid regions of the world [27,28]. Plant production, as well as soil water and nutrient balances, of paddocks (plots) cultivated with groundnut, millet, sorghum, maize and rice has been simulated over three soil profiles and under five different management treatments. This set of factors is variable enough to represent a variety of soil fertility conditions typical of the target agro-ecological belt and the main management treatments which are either widely practised by farmers or commonly tested in experimental agricultural research. Recent crop modeling studies
have performed comparative assessments of the impacts of climate change on these food crops in Sudanian savanna regions [29,30]. However, the integration of such process-based simulation outputs with nutritional, feed and fuel provision biomass indicators has not yet been evaluated. These can be used as indicators of the capacity of agricultural lands to provide the quantities of products necessary to satisfy societies’ demands for nutritious food and fuel, and hence, contribute to better guide the design of land use change research and policies [31].

2. Materials and Methods
2.1. Crop Performance Simulation

2.1.1. The Modelling Platform: APSIM

The APSIM 7.9 modeling platform is a one-dimensional modular environment that simulates plant growth through its mechanistic interactions with soil and atmosphere. It is particularly suitable for assessment of long-term performance due to its emphasis on simulating soil resources dynamics [32].

Water and soil modules of APSIM are further developments of the CERES model [33]. The water balance module (SOILWAT) is a cascading layer model. The initial soil water content is modified at daily timesteps based on soil parameters and water uptake by the plant modules. It accounts for canopy cover and surface residues to modify runoff and reduce potential soil evaporation. The calculation of evaporation is based on potential evapotranspiration (Priestly-Taylor or Penman-Monteith), and that of runoff on the USDA curve number, modified by the effect of tillage practice. Water movement within the soil profile is mediated by three state variables defining the volumetric water content (mm$^{-3}$) for each layer corresponding to: a soil potential of 15 bar (approximately the driest water content achievable by plant extraction), the drained upper limit or field capacity (content of water retained after gravitational flow), and the water content at saturation. Diffusivity coefficients (constant and slope) determine unsaturated flow between adjacent layers. Saturated flow, i.e., the proportion of water above field capacity which will drain to the next deeper layer, is expressed with the SWCON coefficient. A three-pool system consisting of fresh (fom), microbial (biom), and humic (hum) organic matter serves to simulate carbon flows, whereas nitrogen flows are determined by the C:N ratio. Decomposition rate constants are modified by soil moisture and temperature [34,35].

Another independent module deals with the transformations of phosphorus in the soil, although some crop models are not sensitive to it, such as ORYZA. Crop modules specify the growth behavior of specific crops, with the possibility to choose among an array of different cultivars. The crop modules communicate at daily time steps with the resource-supply modules. Different crops planted in the same field have an indirect effect on each other through their influence on the level of resource stocks/fluxes supplied by the radiation, water and nitrogen modules. Finally, a management module simulates the effects of farming practices (such as fertilization, tillage and weeding) on crop and resource-supply modules [36].

2.1.2. Input Data

APSIM requires daily data of four weather variables: incoming radiation, precipitation and minimal and maximum temperature. Data was downloaded from the National Aeronautics and Space Administration’s POWER database (NASA) for the period 1997–2013 at the coordinates of the town of Bolgatanga (10.84° N 0.86° W) in Northern Ghana. The average annual rainfall of the dataset is 1024 mm, concentrated between April and October. This dataset represents the typical climatic pattern of the south Sudanian savanna belt of West Africa.

A soil fertility factor consisting of three soil profiles was introduced to account for the range of the most relevant fertility differentials in this agro-ecological belt. Two soil profiles represent low and medium-fertility conditions of non-hydromorphic soils, ranked as soil fertility 1 and 2, respectively. The data was obtained from soil previously parameterized
Regosols in the APSIM platform [37]. An additional soil profile was defined to represent the hydromorphic that develop along the narrow valley bottoms of Sudanian savanna landscapes. Its chemical properties were defined based on average regional values reported by literature, and its sandy clay texture [38], was taken as base to define its physical properties by averaging the values of the African sand and clay soil profiles provided in the APSIM installation. APSoil parameter values were defined following standard soil texture-based values. SWCON was set at 0.3, for the hydromorphic, sandy clay soil; and at 0.6 for the other two soils, with a sandy loam texture. These values were obtained by averaging the typical of clay and sand, in the case of the hydromorphic soil; and those of loam and sand in the case of the two upland soils [39]. Table S1 in Supplementary Material shows the values of the soil properties used in the simulations.

Management operations and cultivar data of the different crop species were set based on a literature review. In the event that a variable could not be set through literature review, the suggested values of the West African APSIM manual were followed (see Table S2 in the Supplementary Material). The timing of management events for each crop was guided by the farming calendars of the Sudanian savanna zone of Ghana [40,41]. A sowing window of about thirty days was established for each crop. The sowing event is simulated on the first day since the beginning of the sowing window in which at least 20 mm of rainfall have accumulated over the three previous days, and the soil water content is at least 50 mm in the case of millet, sorghum and maize, and 30 mm in the case of groundnut. In the event that this never occurs, sowing is done anyhow by the last day of the sowing window. In the case of rice, the sowing date was established deterministically because it uses another modelling framework, ORYZA, in which sowing windows cannot be defined. Sowing depth was assumed to be 5 cm for all crops.

Cultivar data of millet and maize was collected from cultivar models which are not available in the default APSIM version [24,25]. Among cultivars whose growth behavior is parameterized in APSIM, the most widely adopted in (West) Africa were used. The “medium” duration sorghum cultivar from the APSIM default version was chosen due to the similarity of its outputs with those reported in literature across West Africa. Due to the lack of groundnut and rice cultivar models validated in West Africa, the default “Virginia” model was used, in the case of the former, because its cultivation is widespread in the region, whereas for the former the “local” variety was chosen among the available models of Asian *Oryza sativa* varieties.

Four different rates of mineral fertilizer application were used as intensification factors: 0N-0P, 5N-2P, 20N-7P, 50N-17P, and 100N-33P (units expressed as kg ha\(^{-1}\)). In the case of groundnut, fertilizer rates were 0N-0P, 5N-5P, 15N-15P, 30N-30P, and 45N-45P. Mineral fertilizer application events were simulated in two splits: the first one is applied the same day as sowing and consists of all the phosphorus plus one-third of the total mineral nitrogen (in the case of groundnut, half of the total nitrogen). The remaining mineral nitrogen is applied 35 days after sowing. In the case of rice, three splits are applied: the first one eleven days after sowing, the second split twenty days after the first application, and the third split fifteen days after that. The rate of nitrogen application in rice fields is doubled at each consecutive split.

Additionally, two tillage practices were simulated. Conventional tillage with animal or mechanical traction and hand-weeding was simulated by including a weed crop. The APSIM platform does not include any plant module to simulate the growth behavior of West African weeds. Therefore, the sorghum module was used, as recommended by the developers. It was determined that weeds may emerge up to four times during a sowing window starting the 1st of April and ending the 14th of October. The requirements for weed emergence are the same as those for sowing groundnut, to represent their capacity to emerge under low soil water conditions. Weed density was assumed to be 3.33 plants m\(^{-2}\), with seeds located at 1.5 cm depth. In these simulations, a seed bed is prepared with disc tillage at a depth of 200 mm 23 days before the start of the crop sowing window, killing all of the emerging weed population and incorporating the organic residues into the soil. The
runoff curve number is reduced by 20, requiring 150 mm of cumulative rain to dissipate the impact of tillage. Hand-weeding may occur up to three times during the crop growing period whenever weed biomass is higher than 750 kg ha\(^{-1}\), or no later than 20 days after the (re-)emergence of the weeds. Weeding events remove 90% of the weed population, and the remainder is incorporated into the soil. Under this management configuration, all of the crop stovers are removed from the field at harvest. A second management configuration was set to simulate herbicide-based weed management in combination with no-tillage. In this case, no weed crop was included, no seed bed was prepared before sowing, and only 25% of the crop stover was removed from the field.

2.1.3. Validation of Simulation Outputs

Annual simulation outputs of each simulation were averaged over the entire simulated period and compared with field-based observations in Sahelian, Sudanian, or Guinean savanna agro-ecologies published in scientific literature. Total biomass, grain yield, length of the crop growing period, water cycle components, and soil carbon and nitrogen losses of each paddock were assessed in order to compare the simulated systems to actually practiced cropping systems reported in the literature. In this way, insights can be gained regarding the uncertainty range of the simulation outputs.

2.2. Crop Performance Assessment

The performance of cropping systems was measured with indicators of the benefits potentially derived from the consumption of the crop biomass [31] provided by one hectare of land, from now on referred as area-scale yields.

Benefits derived from biomass consumption were measured as the nutritional yields of grain consumption, the fuel value of stalks, the feed value of leaves, and the local market value (see Table 1). Nutrient content data was retrieved from the UN West African Food Composition Table [42]. Consumption habits were taken into consideration to choose among the different values in the table. Cereals were assumed to be boiled previous to consumption, and groundnuts eaten raw after drying. Rice values were averaged between brown and white rice; and maize values averaged between yellow and white maize.

Table 1. Nutrient content, fuel, feed and market value of cropland biomass.

| Crop  | Nutrient Content | Fuel Value | Feed Value | Market Value |
|-------|------------------|------------|------------|--------------|
|       | cal kg\(^{-1}\)  | Fe mg kg\(^{-1}\) | Zn mg kg\(^{-1}\) | LHV MJ kg\(^{-1}\) | ME MJ kg\(^{-1}\) | $ kg\(^{-1}\) |
| Groundnut | 2370 | 43.0 | 19.0 | - | 7.26 | 0.963 |
| Millet    | 1440 | 59.0 | 11.0 | 15.51 | 5.24 | 0.582 |
| Sorghum   | 1530 | 36.0 | 6.0 | 17.00 | 5.57 | 0.394 |
| Maize     | 1350 | 14.0 | 5.5 | 15.48 | 7.88 | 0.314 |
| Rice      | 1340 | 8.5  | 5.5 | 15.56 | 6.20 | 0.909 |

Fuel value of stalks was expressed as Lower Heating Value (LHV) [43] and the metabolizable energy (ME) of leaves consumed by ruminants was obtained from studies in Mahon (Burkina Faso) [44], with the exception of rice stover, obtained from a study in Niger [45]. The local market value was estimated as the average selling price of the grains in the Bolgatanga market during the period 2007–2013, recorded monthly from the Ministry of Food and Agriculture of Ghana (unpublished), converted into dollars with the average conversion rate of 2013 [46].

Biomass yields were multiplied by the average benefit indicator content of the corresponding biomass compartment to obtain their nutrient, fuel and feed yields, as well as the monetary value of the agricultural production on one-hectare. The ecosystem goods provided by food nutrients has been measured in Nutritional Yield (NY) units. This variable expresses the number of persons who would be able to obtain 100% of their Daily
Recommended Intake (DRI) of a particular nutrient from a food item produced annually on one-hectare (Equation (1)) [18]:

\[ NY_{ji} = \frac{NC_{ij} \times 10 \times y_i}{DRI_j \times 365} \]  

(1)

where \( NC_{ij} \) is the amount of nutrient \( j \) per 100 g of dry matter in crop \( i \). It was measured in calories (cal), in the case of energy, and milligrams in the case of iron (Fe) and zinc (Zn). DRI is the average Daily Recommended Intake of nutrient \( j \). This value has to be multiplied by 10 because NC is expressed in content per 100 g of food; whereas the edible yield \( y \) is expressed in kg ha\(^{-1}\) year\(^{-1}\), and divided by 365 because DRI is a measure of daily intake.

DRI caloric intake was defined as Energy Minimum Requirements and was estimated as 2227 calories per day [47], DRI of iron 16.26 mg per day, and zinc 6.02 mg per day per person, under the assumption of dominant cereal and tuber based diets with insufficient ingestion of fruits, vegetables, and animal products, implying low iron and zinc bioavailability [48]. These values were obtained by weighting the DRI of the different age-sex population groups of the Bolgatanga and Bongo districts of Northern Ghana [49,50] (see Tables S3–S5 in the Supplementary Material).

The requirements of fuel and feed are more complex to calculate. Metabolizable energy requirements are not only species-specific, but are also mediated by the overall nutrient composition of the feed resource. Fuel requirements can be approached through the so-called “useful energy” concept, which refers to the actual heat utilized for the purpose for which fuel is consumed, i.e., cooking. Useful energy cannot be measured directly. Instead, cooking time is typically used as an indicator. Moreover, cooking biomass fuel requirements vary depending on the cooking device and the household size. Therefore, unlike the nutritional yields, the fuel (Equation (2)) and feed (Equation (3)) values of this study express only provisioning levels, not the number of people whose requirements can be satisfied.

\[ \text{Fuel provision}_i = \text{Stalk}_i \times \text{LHV}_i \]  

(2)

\[ \text{Feed provision}_i = \text{Leaves}_i \times \text{ME}_i \]  

(3)

Fuel and feed provision are the fuel and feed output values (MJ ha\(^{-1}\)) of crop \( i \), calculated as the LHV (MJ kg\(^{-1}\)) of the stalks of crop \( i \) multiplied by the harvested stalk biomass of crop \( i \) (kg ha\(^{-1}\)), and as the ME for ruminants (MJ kg\(^{-1}\)) of the leaves of crop \( i \) multiplied by the harvested leaf biomass of crop \( i \) (kg ha\(^{-1}\)), respectively.

In the case of groundnut, it was assumed that all of the harvested aboveground biomass (haulm) was used as feed (Equation (4)).

\[ \text{Groundnut fuel provision}_i = (\text{Stalk}_i + \text{Leaves}_i) \times \text{ME}_i \]  

(4)

Additionally, crop performance was also measured as yield-scale soil carbon losses, i.e., the amount of soil carbon lost to produce one unit of any biomass consumption benefit (Equation (5)). In the context of the study region, where low-input agriculture is widespread, it was considered that soil carbon losses are the most relevant environmental impact of agricultural production, as it compromises landscape-scale and future primary production in a context where soil carbon pools are already low. Therefore, it was considered as a meaningful indicator of the impacts of crop production.

\[ Y_{\text{SOCbal}} = \frac{\text{SOCloss}}{Y} \]  

(5)

where \( Y_{\text{SOCbal}} \) is the yield-scale soil organic carbon (SOC) balance, resulting from the production of one unit of any yield indicator \( Y \) (nutritional, fuel, feed, etc.); \( \text{SOCbal} \) is the soil carbon balance from the soil on one-hectare of land.

This indicator provides a measure for how efficient low input agriculture is in meeting current human demands for biomass products while maintaining soil productive capacities.
for sustaining its biomass provisioning levels. In high input agriculture, the yield-scale SOC balance indicator is less relevant regarding crop species choice by land owners and managers having access to large financial resources, because carbon losses are compensated by external inputs. However, it has impacts at broader spatio-temporal scales. In this case, higher SOC losses of current land use lead to lower soil productivity for the land use following the abandonment of intensive agricultural activities. Trade-offs between the production of the current land use and the potential of the next may affect competing interests among stakeholders.

Both area-scale yields and yield-scale soil balances were synthesized in paddock-specific spider graphs after normalizing the values of each performance indicator (Equation (6)).

\[
N_{ji} = \frac{V_{ji} - V_{j_{\text{min}}}}{V_{j_{\text{max}}} - V_{j_{\text{min}}}}
\]  

where \(N_{ji}\) is the normalized value of indicator \(j\) and crop \(i\); \(V_{ji}\) is the output value of indicator \(j\) and crop \(i\); \(V_{j_{\text{min}}}\) is the value of the worst performing crop regarding indicator \(j\); and \(V_{j_{\text{max}}}\) is the value of the best performing crop regarding indicator \(j\); for each of the simulated paddocks.

3. Results
3.1. Model Results
3.1.1. Grain and Total Biomass Area-Based Productivity

APSIM outputs of total biomass, grain, leaf, and stem yields per hectare under the five simulated levels of management are presented in the Table S6 of the Supplementary Material. Grain yields of maize range between 0.6 and 4.7 t ha\(^{-1}\), and are the highest in all paddocks receiving some amount of mineral fertilizer, except for hydromorphic soils at the highest rates of fertilization. On the other hand, the lowest grain yields across all paddocks are provided by millet, ranging between 0.7 and 2.6 t ha\(^{-1}\). Only groundnut yielded less in hydromorphic soils with low or no amounts of mineral fertilizers, likely as a consequence that this soil type was assumed to have a low phosphorus content, which is the main nutrient limiting the potential growth of legumes. Simulated groundnut yields ranged between 0.7 and 3.1 t ha\(^{-1}\), and they reach their maximum average yield in medium fertility soils at fertilization rates of 15 kg P ha\(^{-1}\), and in hydromorphic and low fertility soils at 30 kg P ha\(^{-1}\). Sorghum yields range between 0.8 and 3.7 t ha\(^{-1}\), and they rank on a median position among the five crops at any paddock. It is the crop providing the highest non-fertilized grain yields on the soil profile with lowest fertility. Rice yields range between 0.8 and 5 t ha\(^{-1}\). It is the highest grain yielding crop in hydromorphic soils provided with no mineral fertilizers and in paddocks receiving 100 kg N ha\(^{-1}\). Rice was the only crop model responding to rates of mineral fertilizer application higher than 150 kg N ha\(^{-1}\), increasing its maximum long-term average yield up close to 5.5 t ha\(^{-1}\). The grain yields of maize and rice are very similar at low and high amounts of mineral fertilizer application, whereas at medium rates (20 and 50 kg N ha\(^{-1}\)), maize grain yields are considerably higher.

Regarding total biomass production, millet and rice provide the highest yields. Both of them produce more plant biomass than sorghum and maize in any of the paddocks. Millet total aboveground biomass productivity ranges 3.6–12 t ha\(^{-1}\). It is the highest biomass-providing crop in fields supplied with low or non-fertilizer, and the second-highest at nitrogen application rates of 100 kg N ha\(^{-1}\), and in hydromorphic soils at rates of 50 kg N ha\(^{-1}\). Rice biomass productivity ranges 2.8–12 t ha\(^{-1}\). It provides the highest biomass at nitrogen application rates of 50 kg N ha\(^{-1}\) and higher. It also provides more biomass than millet in non-hydromorphic soils at nitrogen application rates of 20 kg N ha\(^{-1}\). Sorghum biomass productivity ranges 2.5–7.6 t ha\(^{-1}\). It is the crop providing the lowest biomass at mineral fertilizer application rates higher than 20 t ha\(^{-1}\). At lower rates of mineral fertilizer application, the lowest biomass levels are those of maize, except for hydromorphic soils with low concentrations of available phosphorus, in which the lowest biomass was provided by groundnut. Maize biomass productivity ranges 1.8–8.5 t ha\(^{-1}\). Groundnut biomass
productivity ranges 2–8.3 t ha\(^{-1}\). It is the highest biomass producer at nitrogen application rates of 20 kg N ha\(^{-1}\) in the non-hydromorphic soil profiles, and at rates of 50 kg N ha\(^{-1}\) only rank below rice.

To gain a better understanding of the range of grain yield estimation uncertainty affecting the outputs of this study, the outputs of our simulations have been plotted in a dot graph together with data published in a selection of field-research studies (Figure 1). Yields were plotted against the mineral nitrogen application rate, and soil fertility classes were distinguished based on the similarity of the SOC concentration between the soils where experiments were undertaken and the profiles defined for the simulations of this study.

**Figure 1.** Sorghum simulated vs. published observed grain yields per fertilizer input level and soil fertility class. Numbers within brackets [] ([51–54]) indicate the reference of the publication from which data was retrieved.

The average annual simulated yields of all crops are plausible because they all fall within the observed yield range in West African savannas. Among all the simulated crops, sorghum is the one whose response to mineral fertilizer agrees the best with in-field observations [51–53] (Figure 1). Millet (Figure 2) and groundnut (Figure 3) simulations' responses to different levels of mineral fertilizer application also agree well with most reported observations. However, some differences between simulated yields and those reported by field-based observations must be acknowledged.

Simulated maximum yields of groundnut are slightly lower than most of the observations reported in the literature.

No data was found to validate millet yields in hydromorphic soils without fertilizer application, nor on groundnut yields in hydromorphic soils of the Sudanian savannas. The yield of a West African site with a humid climate was used to compare against the groundnut yields simulated in these paddocks [63].

Maximum yields of maize (Figure 4) are considerably lower than those reported by the reviewed literature. In the simulated medium fertility and hydromorphic soil profiles, maize grain yield reached its maximum at 50 kg N ha\(^{-1}\), despite water-limited yield potentials which have been reported to be reached at higher rates of fertilizer application. On the other hand, maize yields simulated with 50 kg ha\(^{-1}\) of mineral nitrogen are higher than those reported by most of the reviewed articles [70–72]. Therefore, the simulated response of maize to high rates of mineral fertilizer application differs from the response reported by individual studies.
Figure 2. Millet simulated vs. published observed grain yields per fertilizer input level and soil fertility class. Numbers within brackets () ([55–62]) indicate the reference of the publication from which data was retrieved.

Figure 3. Groundnut simulated vs. published observed grain yields per fertilizer input level and soil fertility class. Numbers within brackets ([63–69]) indicate the reference of the publication from which data was retrieved.
Rice production is shown in Figure 5. Right after the 100 kg N ha\(^{-1}\) mark of the x-axis, literature data without information on the rate of fertilizers applied was plotted: maximum and mean plus standard deviation rainfed yields recorded across different savanna sites with a length of the growing period above 90 days [78,79], and average yields of high-yielding farmers [80], without explicit descriptions of the intensity of fertilization. This data helps to assess the plausibility of the simulated yields, given the scarcity of experimental studies on high-input rainfed rice, showing good agreement with the simulated yields of the most productive plots. Moreover, yields at fertilizer application rates of 100 kg N ha\(^{-1}\) are similar to those simulated with CERES at rates of 90 kg N ha\(^{-1}\) in the humid zone of Ghana [81]. Rice yield data at fertilization rates lower than 100 kg N ha\(^{-1}\) have been gathered from one single study [82] conducted in both upland and lowland fields (assumed to correspond to low fertility soils and hydromorphic soils, respectively) in the Sudanian zone of Burkina Faso and Mali. Yields in non-fertilized soils coincide with some of the observations reported in the literature [82,83].
3.1.2. Water Cycle

The different components of the water cycle, i.e., rainfall, runoff, evaporation, transpiration, drainage downwards the 30 cm depth horizon, and soil moisture change were computed as the annual sum of the daily change, and averaged on an annual basis across the simulation period.

The sum of each component of the water cycle within the soil-crop system equated to water inputs (rainfall) in all the simulations with the exception of rice, in which the sum of the water cycle components was 60–80 mm higher than rainfall. Despite the fact that rice paddocks simulate higher evapotranspiration and smaller drainage than any of the other crops, which is expected due to the rice capacity to uptake large amounts of water and its high water use efficiency, the large mismatch between the sum of each of the components of the water cycle within the soil-plant system and the rainfall, suggest that the precise amounts of the water cycle components of rice fields were not properly estimated. Therefore, rice paddocks have been discarded from the quantitative comparison of soil water flows.

Average annual soil moisture change accounted for the lowest amount of the annual water cycle (always inferior to 0.6% of the average annual rainfall). Simulated runoff was very small in all paddocks, between 2% and 5%, probably due to the flat slope assumed in all simulations.

Transpiration ranges between 2 and 20% of annual rainfall, with higher transpiration in groundnuts than in cereals fields in equal paddocks. Among cereals, transpiration is largely driven by total biomass production. Therefore, millet paddocks tend to output higher transpiration values, followed by maize and sorghum. Evapotranspiration ranged between 52% and 68% of total rainfall, and drainage between 30% and 45%. Evapotranspiration and drainage are mainly controlled by crop species and biomass production. For the same crop, higher evapotranspiration rates occur wherever biomass production is higher. Evapotranspiration contributes to more than 60% of the annual water cycle only in groundnut fields supplied with 20 kg N ha\(^{-1}\) or more (and 5 kg N ha\(^{-1}\) in medium fertility soils). The highest evaporation losses on equal paddocks occur in maize fields. Lowest evapotranspiration and, conversely, highest drainage, occurs in sorghum fields, followed by millet. Drainage is also driven mainly by crop species and biomass production, but to a lower degree, because it is influenced by the tillage method.

From a land system perspective, and assuming that drainage and runoff water are effectively used for the satisfaction of human demands, evaporation can be considered the only component of the water cycle that can be accounted as a loss. In this case, crops with higher total biomass production potential and higher plant water use efficiency (WUE) have a better performance. Groundnut, millet and rice are the crops experiencing the lowest evaporation losses at equal soil and management. Despite the precise levels of evaporation simulated in rice paddocks that are subjected to higher uncertainty, due to the above-mentioned shortcoming, relatively low evaporation losses are indeed expected, due to its high water use efficiency and biomass production potential. Conversely, evaporation in maize and (high fertility) sorghum paddocks is higher than in the corresponding paddocks of the other three crops, due to their relatively low biomass production. Differences in evaporation from equivalent paddocks cultivated with different crops can range up to 40–50 mm, and in the case of maize up to 80 mm, corresponding to between 4–5% and 8% more water losses than the crop incurring the lowest losses in each equivalent paddock.

3.1.3. Soil Carbon and Nitrogen Stock Changes

All paddocks experienced net decrease of soil carbon and nitrogen by the end of the simulated period (Table 2). Among the three factors of agronomic productivity assessed in this study (crop species, management and soil), the wider differences in the levels of soil nutrient loss are given by the soil profile.
Table 2. Range of simulated nutrient losses for the different production factors.

| Soil                  | Average Annual SOC Losses | Average Annual N Losses |
|-----------------------|---------------------------|-------------------------|
|                       | Min (g kg⁻¹)              | Max (g kg⁻¹)            |
| Hydromorphic          | 0.356 (0.0719)            | 1.023 (0.2068)          |
| Medium fertility      | 0.157 (0.0340)            | 0.450 (0.0978)          |
| Low fertility         | 0.033 (0.0069)            | 0.256 (0.0544)          |
| Management            |                           |                         |
| 0N-Disc tillage       | 0.155 (0.0330)            | 1.023 (0.2068)          |
| 5N-Disc tillage       | 0.146 (0.0311)            | 1.022 (0.2064)          |
| 20N-Disc tillage      | 0.088 (0.0187)            | 0.929 (0.1877)          |
| 50N-No tillage        | 0.078 (0.0165)            | 0.926 (0.1871)          |
| 100N-No tillage       | 0.033 (0.0069)            | 0.925 (0.1870)          |
| Crop                  |                           |                         |
| Maize                 | 0.145 (0.0307)            | 1.023 (0.2068)          |
| Sorghum               | 0.126 (0.0268)            | 0.847 (0.1712)          |
| Groundnut             | 0.078 (0.0165)            | 0.910 (0.1877)          |
| Rice                  | 0.097 (0.0205)            | 0.474 (0.0958)          |
| Millet                | 0.033 (0.0069)            | 0.613 (0.1238)          |

Maize cultivation drives to higher soil nutrient losses than any other crop under the same growing conditions (see Table S6 in the Excel Spreadsheet of the Supplementary Materials). However, these losses are not much higher than the second or third crop in this category, which is either millet or groundnut (under low fertility conditions) and sorghum (under high fertility conditions). At low rates of fertilizer application (5 kg N ha⁻¹) and high rates of biomass export, rice paddocks incur lower soil nutrient losses than any other crop. Also at fertilization levels of 20 and 50 kg N ha⁻¹ in hydromorphic and medium fertility soils. However, in low fertility soils subjected to this management the lowest soil nutrient losses occur in groundnut and millet fields. At fertilizer application rates of 100 kg N ha⁻¹, fields cultivated with millet experience remarkably lower nutrient losses than fields cultivated with any other crop species, with the exception of hydromorphic soils, where nutrient losses of rice cultivation are similar.

In hydromorphic soils, the levels of soil nitrogen losses show their lowest sensitivity to management in rice paddocks, followed by sorghum and maize. The variability of nitrogen losses across different management prescriptions of groundnut is twice the variability of sorghum and maize, and more than three times higher than that of rice. Nitrogen losses of soils cultivated with millet display the highest sensitivity to management, being almost twice more sensitive than groundnut. In medium fertility soils, the soil nitrogen balance of soils cultivated with sorghum is almost the same (2–4 kg ha⁻¹ year⁻¹, regardless of management. The highest sensitivity is displayed by paddocks cultivated with millet (12–32 kg ha⁻¹ year⁻¹), displaying a variability twice as high as that of groundnut paddocks, with a similar level of nitrogen losses in low input agriculture combined with removal of all plant biomass, but experiencing twice the losses (25 kg ha⁻¹ year⁻¹) at high levels of intensification of plant biomass returns. In low fertility soils, the soil nitrogen balance of soils cultivated with rice is almost the same (11–13 kg ha⁻¹ year⁻¹, regardless of management. Sorghum also shows low sensitivity to management. The highest sensitivity is displayed by paddocks cultivated with millet (2–21 kg ha⁻¹ year⁻¹). Groundnut and maize display a medium variability of 10 kg ha⁻¹ year⁻¹ between the least and most intensive management.

Regarding the magnitude of absolute nutrient balances, our simulations agree with only a few studies. For example, in Ethiopian highland savannas with annual rainfall equal to Sudanian savanna regions, N losses of maize fields in hydromorphic soil (1.1% SOC) were 73 kg N ha⁻¹ year⁻¹ in unfertilized plots and 60 kg N ha⁻¹ year⁻¹ in plots receiving 44 kg N fertilizer [84], only slightly lower than the 97 and 88 kg N ha⁻¹ year⁻¹ in the equiva-
lent management of our simulated hydromorphic soils (1.4% SOC). In Southern Uganda, N losses in maize fields without fertilizer application and soils with SOC concentrations above 2% range between 84 and 104 kg N ha$^{-1}$ year$^{-1}$ [85], being the same magnitude as our simulations. In sandy soils of Northern Nigeria with SOC content lower than in any of the studied profiles (0.2%), soil nitrogen losses of millet-sorghum-legume cropping systems ranged between 1 and 71 kg N ha$^{-1}$ year$^{-1}$ [86]. Those values fall within the simulated range in millet (2–69 kg N ha$^{-1}$ year$^{-1}$) and sorghum (11–81 kg N ha$^{-1}$ year$^{-1}$) fields, only being slightly higher in groundnut fields (up to 89 kg N ha$^{-1}$ year$^{-1}$ and 72 kg N ha$^{-1}$ year$^{-1}$ in fields receiving 45 kg N ha$^{-1}$). Losses in the simulated groundnut fields are also higher than in bean fields analyzed in the research conducted in Ethiopian savanna, where they ranged between 51 kg N ha$^{-1}$ year$^{-1}$ non-fertilized plots and 19 kg N ha$^{-1}$ year$^{-1}$ plots receiving 44 kg N ha$^{-1}$ [84], and Southern Uganda, ranging between 40 kg N ha$^{-1}$ year$^{-1}$ and 20 kg N ha$^{-1}$ year$^{-1}$ [85]. Conversely, in non-hydromorphic soils, N losses in groundnut fields range between 10 and 35 kg N ha$^{-1}$ year$^{-1}$, being slightly lower than those reported by the literature in annual legume fields.

A more extensive review shows that the general response of APSIM soil dynamics to organic matter inputs is weaker than field observations, regardless of the crop type. Results of hydromorphic soils cultivated over three years in Senegal indicate that soil C and N losses can be prevented with the addition of around 5 t ha$^{-1}$ of straw return [87]. Simulated rice residue returns managed at maximum fertilizer intensification is close to that level (4.7 t ha$^{-1}$). Millet fields on hydromorphic soils receiving 20 kg N ha$^{-1}$ or more, and 100 kg N ha$^{-1}$ in non-hydromorphic soils, receive 5–7 t ha$^{-1}$ of crop residue. The rest of the paddocks receive annual quantities of crop residue well under 5 t ha$^{-1}$. Despite factorial simulations indicating that, indeed, the rate of biomass production and, hence, the rate of biomass return, minimize the depletion of soil nutrient pools, all paddocks experienced nutrient losses. Productive agricultural fields subjected to continuous cropping can maintain, and even increase, soil nutrient pools under appropriate integrated soil management strategies [85,87,88]. Preventing soil nutrient losses can be even achieved by only applying mineral nitrogen fertilizer [89], although the realization of such outcome can be restricted by initial soil conditions [90]. Soil nitrogen balance of non-fertilized maize cultivation in Southern Benin was 38 kg N ha$^{-1}$ year$^{-1}$ [88], the same rate as our simulation of non-fertilized, medium soil fertility. However, this study found positive soil nitrogen balance with the addition of medium amounts of mineral fertilizers. Regarding nutrient cycling in rice fields, it seems that APSIM simulated SOC balances more accurately than soil N balances. SOC losses of rice fields in Senegal averaged 0.066 g C kg$^{-1}$ year$^{-1}$, and soil nitrogen losses averaged 0.02 g N kg$^{-1}$ year$^{-1}$ [87]. The rate of SOC depletion falls within the range simulated in rice paddocks (0.0205 up to 0.0958 g C kg$^{-1}$), but the simulated N loss is at least between two and ten times lower (0.0093–0.0023 g N kg$^{-1}$ year$^{-1}$). The slow depletion of APSIM soil nutrient pools compared to observations can be found also in other crops. For example, the nitrogen depletion rate in the non-fertilized millet paddock with the highest N losses (0.0139 g kg$^{-1}$ year$^{-1}$) is five times lower than the losses averaged across four years 0.0725 g kg$^{-1}$ year$^{-1}$ in SW Niger [91]. In sorghum fields fertilized with 50 kg N ha$^{-1}$, the rate of N depletion was 13–25 kg N ha$^{-1}$, three times lower than observations in the Sudanian savanna zone of Burkina Faso (30–70 kg ha$^{-1}$) [92].

### 3.2. Multi-Criteria Comparative Performance of Potential Benefit Yields

Here, the performance based on several indicators of potential benefits derived from biomass use is assessed, both on an area- and a yield-scaled basis.

Groundnut performs better than any cereal across most indicators and paddocks. Only its fuel yield is lower than the other crops, and this occurs because only traditional cooking technologies are considered to define fuel yields and it has been assumed that its stems are allocated for feed use. In a scenario of widespread adoption of gasification technologies, groundnut contribution to regional fuel yields could be higher than cereal crops, due to the high fuel potential of its husks. Additionally, if other uses of biomass-based fuel different
from cooking were considered, the fuel yield of groundnut production would be also high, due to the high biodiesel potential of the nuts. However, in this study it has been assumed that all the edible parts of crops are allocated to human food consumption.

On an area basis, the comparative performance of the potential benefits derived from biomass use is similar to those of total biomass and grain, particularly in regards to the inter-comparison between cereal crops. Millet and rice provide higher feed and fuel yields than maize and sorghum. Cereal crops providing higher grain yields provide higher caloric yields, which is the scarcest nutrient yield of cereal production. The concentration of zinc and iron in millet and sorghum is significantly higher than in maize and rice, and consequently, the relative performance on the provision of these nutrients is better than compared to the grain productivity. This is particularly the case with iron, which is the scarcer of the two micronutrients. In this case, millet and sorghum provide higher nutritional yields than maize and rice, regardless of the paddock.

Groundnut and rice have a market value significantly higher than the other crops. Therefore, the total market value of their production is higher than the other crops, regardless of the paddock. The market value of groundnut production is higher than that of rice in non-hydromorphic soils supplied with 20 kg N ha\(^{-1}\) or less. At rates of 50 kg N ha\(^{-1}\) the market value of the production of both crops is not significantly different in non-hydromorphic soils. The market value of rice production is significantly higher than groundnut in hydromorphic soils and in any soil supplied with 100 kg N ha\(^{-1}\). There are no wide differences between the market value of the other three cereal crops, particularly at fertilizer application rates of 20 kg N ha\(^{-1}\). Maize provides the highest market value in comparison to sorghum and millet at fertilizer application rates of 50 kg N ha\(^{-1}\), and the gap is reduced at rates of 100 kg N ha\(^{-1}\). However, the market value of maize production is lower than that of the other two cereal crops in fields supplied with none or low amounts of fertilizer.

Figure 6 presents the multi-criteria biomass use performance of the production of the four cereal crops across different simulation paddocks. Groundnut has been omitted in these graphs to ease the visualization of cereal performance because it performed better in all indicators (with the exception of fuel) and across all paddocks. See the Supplementary Material to visualize the comparison of the complete array of paddocks, including the yield-scaled SOC balance (Figure S1a–e) and including groundnut performance (Figure S2a–e).

Due to the different response of crops to fertility conditions (yield potential), caloric yield (CalY) differences between crops widen the higher the fertility condition is. Sorghum is the highest CalY-yielding crop without N fertilizer application, and the lowest in the poorest fertility soils is maize, providing 69% of the CalY yield of sorghum. In more fertile soils, millet is the lowest CalY-yielding crop, providing roughly 80% of the yield of sorghum. At fertilizer application rates ranging 5 to 50 kg N ha\(^{-1}\), maize is the highest CalY-yielding crop, and comparatively more as the rates of fertilizer input increase. At 5 kg N ha\(^{-1}\), caloric yields of sorghum and rice are very similar to those of maize (83–96%, depending of soil condition), whereas those of millet are between 67% and 84%: the higher the soil fertility is, the bigger the CalY gap. At higher rates of mineral fertilizer, millet CalY yield can be as low as 38% of that of maize. At 100 kg N ha\(^{-1}\), the gap between the CalY yield of maize and that of the other crops decreases. Maize and rice CalY yields are no significantly different at this level of mineral fertilizer intensification, whereas sorghum yields between 61% and 84% of those crops (the higher the soil fertility the smaller the gap), and millet CalY yield lies around 45%, regardless of the soil fertility class.
Comparative performance of yield-scaled SOC balance indicates how much SOC loss is avoided (taking as reference the maximum SOC loss per paddock) to provide one unit of biomass-based product, benefit or income. In no input fertilizer agriculture, the performance of maize relative to the other crops is lower, and rice performance better, than if they were measured on an area-scale basis. Sorghum performance on yield-scaled SOC balance basis relative to millet is better in non-hydromorphic, and worse in hydromorphic soils, than on an area-scale basis. The same occurs in fertilizer based agriculture, at rates of 20 kg N ha$^{-1}$, although in this case the relative performance of not only rice, but also millet, is better than the other two cereal crops. Indeed, the perception of millet performance under a yield-scale basis of SOC balance is enhanced in comparison to the area-scale basis more than that of rice at fertilizer application rates of 100 kg N ha$^{-1}$. In any case, millet

| Fertilization rate | Soil fertility rank |
|-------------------|--------------------|
| 5N-2P             | 1                  |
|                   | 2                  |
|                   | 3                  |
| 20N-7P            |                    |
| 50N-17P           |                    |
remains the crop providing the lowest caloric yield, both on an area-scaled yield and on a yield-scaled SOC balance basis.

4. Discussion

4.1. Model Performance

This study shows the opportunities of using process-based crop models to perform ex-ante multi-criteria yield and impact assessments. Input data regarding climatic variables, soil properties and management have been chosen based on extensive literature review, trying to represent growing conditions typical of Sudanian savanna agro-ecologies. However, we acknowledge that such conditions may vary widely within this agro-ecological belt. Observed measurements have not been taken, thus, it has not been possible to evaluate if parameter optimization was necessary. Therefore, until further steps into the multiple-crop parameterization in these agro-ecologies are undertaken, the output results of this study must be taken with caution before extracting concluding evidence of the crop comparative performances. Meanwhile, a comparison between the output results of this study with observed measurements can help to better understand the uncertainty range of each indicator.

4.1.1. Biomass and Grain Yields

Non-fertilized paddocks simulate higher grain yields than those reported in the literature. This can be explained because the cultivar set typically used by farmers is more diverse than the simulations, in which only one cultivar is sown per paddock. Planting of one single cultivar may maximize yields under optimal growing conditions. However, given the high inter-annual climate variability, available farm labor at the right time is often limited. The APSIM sowing routine, as defined in our simulations, assumes that labor is always available, therefore maximizing the performance of single cultivar fields, whereas in smallholder agriculture diverse cultivar set choices are frequently preferred due to their higher yield stability, albeit lower maximum expected yield.

Reported maize yields vary widely between studies. This indicates that maize is very sensitive to growing conditions, and more than it can be expressed with the limited set of genotype, climate, soil and management factors used for our simulations. Wide differences are expected to arise at the local scale due to slope position as well as between regions, even within the same climatic zone and similar soil characteristics [75]. One major factor limiting maize crop yield is the depth of soil root penetration, which in Sudanian savannas is limited by the common presence of laterite layers near the soil surface [93]. However, it is worth noting that maize yields in the simulated medium fertility and hydromorphic soil profiles reached their maximum at 50 kg N ha$^{-1}$, despite water-limited yield potentials have been reported to be reached at higher rates of fertilizer application. In the case of the hydromorphic soil, the fact that its different state variables and parameters were defined from different sources might have resulted in a simulated profile which does not accurately describe the behavior of soil water in the valley bottoms of Sudanian savannas. Changing the soil parameters that define the behavior of soil water in APSIM or the use of additional cultivars might help to simulate the wider range of maize yields across West Africa. In any case, the maximum average maize yield of the simulations matches that of the widely adopted Obatanpa cultivar obtained by high-yielding farmers in Ghana (4.28 t ha$^{-1}$) [94], meaning that the simulated yields can be representative of the highest expected yields in the current context of resource endowment in West Africa.

Published data to validate our simulated rainfed rice yields is scarce because most studies either refer to irrigated fields or do not provide explicit information on fertilizer intensification levels. Simulated agronomic N use efficiency, i.e., the increase in grain yield per added unit of N fertilizer, ranged 29–45 kg kg$^{-1}$, which is larger than common observations, ranging between 5 and 27 kg kg$^{-1}$ across West Africa for the broadcast split application method [95]. This is likely caused by the structure of the rice model, which has not yet been adapted and validated under West African conditions [96].
Methodological differences, as well as the particular growing conditions, among each of the reviewed literature may also explain deviations among yields reported by different studies as well as in relation to our simulations. Moreover, it must be taken into consideration that the simulated yields are a long-term average, whereas observations reported in the literature refer to one or only a few growing seasons. This might have influenced the higher minimum and lower maximum yields of the simulations in relation to the range of values found across the literature.

4.1.2. Water Cycles and Water Use Efficiency

The simulation outputs describing the volumes of the water cycle components and soil carbon and nitrogen stocks were evaluated also against values reported in the literature. However, field-scale observations or estimations of these variables in West African savanna agroecology are scant.

Factorial experiments estimating the water cycle components under the cultivation of different crop species do not exist to our knowledge. The few available comparative studies at the field scale focus on the water efficiency of agricultural production, rather than on the whole water cycle. Quantifications of the whole water cycle are usually conducted at the hydrological basin scale. However, the output values of these studies cannot be directly compared to those of one-dimensional dynamic crop models, because perennial vegetation, water bodies, bare land, and human-made impermeable surfaces have very different impacts on the water cycle than croplands. Additionally, the spatial pattern of the orography, soils and vegetation distribution plays an important role in water movement. Therefore, the volumes of the water cycle components vary widely between basins.

Evapotranspiration across different hydrological catchments in savanna regions of central West Africa ranges between 60% and 74% of the annual rainfall; runoff between 6% and 13%; and infiltration between 18% and 37%, with less runoff in the catchments and more area covered by uncultivated savanna. Higher infiltration values correspond to basins with a higher proportion of natural vegetation cover [97–100]. Drainage, which constitutes only a fraction of the infiltrated water, ranges between 30 and 45% (excluding rice) in our simulations. The simulated runoff is very low (2–5% of the annual water cycle), whereas values above 10% in cropped fields with flat topography, and even close to 40%, are common [101,102]. The low runoff values simulated in this study might be derived both from the profile description and the model structure itself, which may overestimate soil water content [103] and may result in an underestimation of runoff. Simulated evapotranspiration values above 74% only occur in rice fields, whose model seems to misrepresent the total volume of the annual water cycle. Values above 60% only occur in highly productive groundnut fields, driven by transpiration, and values around 60% in maize fields, in both extremes of its productivity range, are driven by a mix of relatively low transpiration and high evaporation. In the rest of the fields, evapotranspiration ranges between 52 and 58% of the annual rainfall which, in the case of sorghum, agrees well with observations (50–56%) in the Sudanian zone of Burkina Faso [102].

The comparison of crop production with water use is reported in literature through a variety of indicators. Assessing the amount of grain (or total biomass) production to the water used by the crop is known as water use efficiency (WUE). In crop physiology, it is understood as the rate of carbon assimilation or grain yield per unit of water transpired. In agronomy, a more meaningful indicator is the ratio of biomass or grain production per unit of evapotranspiration water during the crop growing period, which is defined as crop water productivity, although some studies also call it WUE. Finally, rainwater use efficiency (WUEr) of land use is more meaningful in landscape approaches because it serves to compare the annual water evaporated and used by the vegetation growing on a piece of land, serving as a quantitative indicator of the trade-offs between biomass production and annual water yield. Crop-wise assessments of either rainwater or evapotranspiration use efficiency are very scant, and reviews must be conducted carefully because of the ambiguity of the concepts across the literature. In this study, we use the WUE concept to
refer to the amount of crop production per unit of water consumed by croplands during the crop growing period.

The range of simulated rice agronomic WUE varies widely, which has also been observed in rainfed rice in Northeast Thailand (2.1–10.3 kg grain mm\(^{-1}\) in the simulations vs. 0.5–10.9 in the reported observations). The range of WUE\(_r\) (1.3–8.0 kg grain mm\(^{-1}\)) also falls within the range of observed values (0.6–8.9 kg grain mm\(^{-1}\)) \([104]\). In hydromorphic soils, simulated rice WUE\(_r\) ranges 3.3–8.0 kg grain mm\(^{-1}\), agreeing with observations in Senegal (4.9–7.9 kg grain mm\(^{-1}\)) \([87]\). Simulated WUE of maize grain production is higher than rice, agreeing with a global meta-analysis \([105]\). Simulated WUE of maize biomass production is lower than millet, and their relative difference agrees with a factorial experiment of irrigated agriculture in a warm arid environment \([106]\). Both simulated agronomic WUE and WUE\(_r\) of millet are similar to field studies in SW Niger \([91,107–109]\) and Northern Ghana \([110]\). The simulated WUE of groundnut is similar to that of another annual legume, soybean, in the derived savanna zone of Nigeria \([111]\). The simulated transpiration efficiency of sorghum is higher than that of millet and groundnut, which agrees with experimental results. However, groundnut transpiration efficiency can vary widely \([112]\), whereas in our simulations the range is narrower.

Hence, crop water use was fairly well simulated, particularly in the comparison between crop species. However, runoff in our APSIM simulations seemed to be underestimated, or at least did not display the expected wide range of runoff values. Conversely, drainage (and infiltration) seem to overestimate the expected drained water quantities under croplands. Although the errors in runoff and drainage may counteract each other for the estimation of water yields, relevant to landscape extent ecosystem service assessments, the low amounts of runoff would result in underestimations of erosion. Therefore, the soil water available for crop growth might be overestimated, while nutrient loss is underestimated, indirectly increasing simulated plant production. These results might be the result of our configuration of the APSIM simulations. Additional simulations shall be conducted changing the values of runoff-related input variables.

4.1.3. Nutrient Cycles and Nutrient Use Efficiency

The variability of the soil nutrient balances of our simulations was much narrower than observations reported in the literature. Also, the sign of the balance varies across literature, whereas all the simulation paddocks experience net decreases. For the same crop and management, nutrient losses are highest in the hydromorphic soils, and higher in the medium-fertility than in low-fertility soils. For the same crop and soil type, nutrient losses tend to be inversely related to the amount of fertilizer applied and biomass returned to the soil, but these factors have a lower effect on nutrient losses than soil profile or crop specie. These results indicate that keeping plant biomass in the field, combined with the application of external fertilizing inputs, compensates the higher amounts of plant nutrient uptake incurred by high-yielding agriculture, but absolute nutrient balances are mostly determined by the initial nutrient pool and rates of biomass removal. This agrees with observations in other African savanna regions on the short- \([113]\), and medium-term \([90]\), as well as long-term (90 years) APSIM simulations in semi-arid Australia \([114]\). However, this study reported soil carbon accumulation over time, which was not simulated in any of our paddocks.

Contrary to these studies, a recent review has found that the addition of carbon inputs plays a far more important role in increasing soil carbon stocks than soil texture or initial soil carbon pool in tropical croplands. This effect is particularly strong in fields supplied with external sources of organic matter. Other management practices not involving the addition of organic matter may drive even higher SOC accumulation rates, namely rotations and reduced tillage with the addition of mineral fertilizer \([115]\). However, as opposed to the results of that review, our simulations of reduced tillage systems in combination with the addition of mineral fertilizers and crop biomass return resulted in net decreases in soil carbon stocks. Our simulations did not contemplate different levels of manure application
because it was assumed that it is not a management strategy that can plausibly be adopted in the majority of the fields of the region given the general degradation of the primary production capacities of West African ecosystems [2,116,117], which limits the available sources of organic amendments across the landscape. Nevertheless, this trend might be reversed, thus subsequent APSIM simulation studies can include factors such as higher levels of carbon inputs, as well as different crop rotations involving perennial vegetation and livestock to assess the performance of land and biomass use alternatives.

The comparison with reported field observations indicates that soil nitrogen dynamics are more inaccurately simulated in fields cultivated with groundnut. This might be due either to inconsistencies in APSIM to simulate N dynamics in legume fields [118] or because the prescribed fertilizer rates were different than those of cereals.

A possible reason explaining why the simulated soil nutrient dynamics may not properly capture the variability of nutrient balances observed across African savannas is because in the agro-ecosystems many cropping fields are selectively tilled with hoes, which is a less invasive technique than the broadcast tillage resulting from animal or mechanical traction plowing [119], as it is typically simulated in one-dimensional models. Finally, it must be pointed out that, despite significantly higher nutrient losses occur in the hydromorphic soil, regardless of the management treatment, this is likely to be driven by the higher levels of nutrient uptake by plants combined with biomass exported from the system, more than by the soil type itself. This “soil type effect” is weakened (and might be even reversed) in actual landscapes because the model does not account for the spatial patterns of nutrient transport and deposition that operate at landscape and regional scales. Hence, the simulation of soil nutrients’ stock balances in hydromorphic soils was not properly simulated, because it did not account for the role of valley bottoms as nutrient-importing areas.

4.2. Crop Multi-Criteria Performance Assessment and Its Implications for Rural Savanna Economies

The multi-criteria assessment of potential benefits derived from biomass consumption shows that each crop fulfils a role in the economy of rural West African savannas. Crop performance is highly determined by both soil fertility and management. Rice and millet perform better in more indicators than sorghum and maize across all paddocks. However, not all benefits shall be considered of equal relevance. Caloric yields shall be considered, in principle, of higher importance, because they are lower than iron and zinc yields. In this regard, millet performs worse than any other crop, regardless of the soil-management context, whereas maize performs the best, assuming accessibility to fertilizers, regardless of the soil type. Under the same growing conditions (understood as the same combination of soil fertility and management practices), rice can satisfy caloric requirements at similar levels compared to maize, although it provides the lowest iron yields. Cash revenues can be considered, together with caloric yield, the most important benefit provided by the production of agricultural biomass because it allows to purchase other foods and access health and education services. Maize and rice provide equal or higher cash revenues compared to millet and sorghum at medium to high rates of fertilizer application. However, the indicator provided in this study is the market value of production, rather than net revenue, and therefore cannot accurately describe the cash benefits provided by each crop. Moreover, access to fertilizers in the context of West African savanna smallholder farmers is limited; therefore, sorghum is essential to maximize food provision. Furthermore, food security in the region highly relies on solid biomass fuel for cooking and the family economy on cash income provided by livestock sales. Therefore, the fuel and feed yield amounts provided by each land use option are also relevant. Rice and millet are the best-performing crops in this regard.

Given the chronic food insecurity situation in which a large proportion of the population of the region lives, it is necessary to increase the share of land use options that provide higher caloric yields. Therefore, the increased adoption of high maize and rice seems a prerequisite to enhance food security, continuing the business-as-usual pattern
over the last three decades. Maize could replace millet and sorghum as the main rainfed cereal. However, the soil water and nutrient balance of maize are more negative than the other typical rainfed crops. Therefore, the success of such land use strategy to enhance food security will be determined by the universal and reliable availability and accessibility of fertilizers, which so far has not been achieved in West Africa. The realization of this condition is more likely to occur in a scenario of higher diversification of the economy and off-farm job opportunities, to enable the increase of the investment capacity of farming households, as well as the country as a whole to purchase/produce fertilizers [120]. Additionally, because the benefits of fertilizer-based rainfed agriculture are subjected to a higher yield variability, this scenario shall also include better storage facilities and distribution mechanisms [121,122].

On the other hand, despite the caloric yield of all of the main food crops cultivated in rural West African savannas is lower than their iron yield, this only occurs by considering the average population requirements, but it does not apply to all groups within the population. For example, 1.75 kg of either maize or rice can provide the stipulated daily minimum energy requirements of women aged 30–50; however, 2.1 kg of maize and 3.46 kg of rice would be necessary to match their iron DRI. The difference is even wider for women under the age of 30 years, as well as for pregnant women because the iron and zinc yields for infants aged less than one year that could be provided by maize or rice is also lower than their caloric yield. Therefore, transitioning towards cropping systems that are more dominated by maize and rice could exacerbate nutritional security problems, leading to higher anemia prevalence, and even mortality, rates.

Finally, climate change likely diminishes the suitability of Sudanian savannas for the cultivation of maize [123], as its potential productivity decreases more than that of either millet or sorghum [29]. Another factor that may play an important role in reorienting the business-as-usual approach of expanding the area of high-yielding crops is fuel scarcity. In the plausible scenario of increasing demand for solid biomass fuel and decreasing availability of firewood per capita, crops that provide higher amounts of non-food biomass will become more valuable in comparison with the present.

Meeting the primary goal of increasing caloric provision per capita shall be rather driven by increased cultivation of grain legumes. As it was shown by the results, groundnuts provide higher yields of the three assessed nutritional indicators than any of the cereal crops, in addition to higher feed yields. This applies to other annual legumes too, although this does not mean that legumes can solve alone the problem of food security. The principle of promoting crop diversity still is valid, because legume-dominated diets can result in health problems due to their high-fat content. A promising land use strategy to increase nutritional yields, and biomass production in general, is the relay cropping of annual legumes [124]. This strategy is not foreign to the native land use system of the West African savannas and should be further promoted for wider adoption and adaptation to the particular context of each region and farm.

5. Conclusions

Over the last years, a variety of dynamic crop models have been validated and widely applied to assess crop yields in West African savannas, increasing the body of available data and the accuracy of crop production simulation in these regions. Such progress in crop science can be used to improve our understanding of the capacity of agro-ecosystem services to support food security and the sustainable improvement of livelihoods through indices of biomass qualities such as nutrient contents, heating values and metabolizable energy.

This study used the modeling platform APSIM to simulate and compare the performance of the main food crops of the Sudanian savannas under equal soil fertility conditions and mineral nitrogen application intensities. It showed how this platform can be fed with readily accessible data to evaluate the food, feed and fuel provision trade-offs incurred by different crop choices. This can be useful as a low-cost data-generating technique to serve
as input of scenario design exercises in a wide variety of applications, such as potential food nutrients and biomass fuel availability assessments.

Simulated biomass and grain yields fell within the range of plausible values, although they tend to be higher than those reported by observations of field experiments reported by literature. Simulated upland rice yields were significantly higher than in any of the reviewed publications. The yields of the rest of the crops in comparison with their counterparts under similar growing conditions agreed well with observed values. However, the simulated output of some management options could not be validated because of the lack of experiments addressing them. It is the case of low-input millet or rice cultivation in highly fertile soils.

Maize and, in soils with lower fertility conditions, sorghum, are key crops to close the gap between the increase of caloric provision and demands. However, a decrease in the provision of iron would result in a general worsening of health status among the population. This could happen in the case of a general substitution of millet and sorghum with maize or rice, because these two high-yielding crop species are less efficient in meeting the iron requirements of young and adult women than in meeting their caloric requirements. Millet is the most efficient crop in this regard. Moreover, it provides high biomass yields, which can be key in contexts of fuel scarcity. Therefore, we recommend a increased focus on this crop by land use and value chain development policies, in parallel to landscape approaches that maximize the regional production of nutritious food and fuel by improving the spatial allocation of crop species.

Some management operations that are nowadays practiced or widely promoted for their yield and sustainability improvement potential were not assessed, such as cereal-legume intercropping and rotations, green manuring, tied ridges, or micro-fertilization. Subsequent assessments must exploit the capabilities of APSIM to simulate these management practices.

Additionally, the generated data can be used as input of spatially-explicit land cover-based assessments. This could provide valuable information in strategic and participatory land use planning processes, as well as to appropriately size agro-industrial investments. However, this requires a previous evaluation of the spatial extent and the range of soil fertility spatial distribution uncertainty which is acceptable to evaluate the issue under concern. Water flows and nutrient budgets were not simulated as accurately as plant production. Therefore, the use of its plant production outputs in land use planning processes can be complemented with models specifically designed for the simulation of water or soil nutrient cycles, to more properly assess crop yield sustainability.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land10080827/s1, Table S1: Physico-chemical properties of the soil profiles, Table S2: Management and cultivar data, Table S3: Energy (kcal) average Daily Recommended Intake per age and sex cohort, assuming medium activity levels diets of the population of Bolgatanga Municipal and Bongo districts, Table S4: Iron (Fe) Daily Recommended Intake per age and sex cohort, assuming 10% bioavailability diets of the population of Bolgatanga Municipal and Bongo districts, Table S5: Zinc (Zn) Daily Recommended Intake per age and sex cohort, assuming moderate zinc bioavailability diets of the population of Bolgatanga Municipal and Bongo districts, Figure S1: Multi-criteria yield assessment of cereal crops on an area-scaled basis (per hectare) and yield-scale SOC balance-basis (per unit of SOC loss), Figure S2: Multi-criteria yield assessments of all crops, including groundnut, on an area-scaled basis (per hectare) and yield-scale SOC balance-basis (per unit of SOC loss), including groundnut, Table S6: Annual average (16 years) biomass, nutritional, fuel and feed yields; components of the water balance; soil carbon and nutrient balance; of continuous cropping simulated with APSIM.

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Data Availability Statement: Files containing the input and output data of the simulations are provided in the digital version of this publication.

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References

1. Machwitz, M.; Gessner, U.; Conrad, C.; Falk, U.; Richters, J.; Dech, S. Modelling the Gross Primary Productivity of West Africa with the Regional Biomass Model RBM+, using optimized 250 m MODIS FPAR and fractional vegetation cover information. Int. J. Appl. Earth Obs. Geoinf. 2015, 43, 177–194. [CrossRef]

2. Fetzel, T.; Niedertscheider, M.; Haberl, H.; Krausmann, F.; Erb, K.-H. Patterns and changes of land use and land-use efficiency in Africa 1980–2005: An analysis based on the human appropriation of net primary production framework. Reg. Environ. Chang. 2016, 16, 1507–1520. [CrossRef]

3. Weinzettel, J.; Hertwich, E.G.; Peters, G.P.; Steen-Olsen, K.; Galli, A. Affluence drives the global displacement of land use. Glob. Environ. Chang. 2013, 23, 433–438. [CrossRef]

4. Herrmann, S.M.; Brandt, M.; Rasmussen, K.; Fensholt, R. Accelerating land cover change in West Africa over four decades as population pressure increased. Commun. Earth Environ. 2020, 1. [CrossRef]

5. Adam, M.; MacCarthy, D.S.; Traore, P.C.S.; Nenkam, A.; Freduah, B.S.; Ly, M.; Adiku, S.G.K. Which is more important to sorghum production systems in the Sudano-Sahelian zone of West Africa: Climate change or improved management practices? Agric. Syst. 2020, 185, 102920. [CrossRef]

6. Faye, B.; Webber, H.; Diop, M.; Mbeye, M.L.; Owusu-Sekyere, J.D.; Naab, J.B.; Gaiser, T. Potential impact of climate change on peanut yield in Senegal, West Africa. Field Crops Res. 2018, 219, 148–159. [CrossRef]

7. Freduah, B.; MacCarthy, D.; Adam, M.; Ly, M.; Ruane, A.; Timpong-Jones, E.; Traore, P.; Boote, K.; Porter, C.; Adiku, S. Sensitivity of Maize Yield in Smallholder Systems to Climate Scenarios in Semi-Arid Regions of West Africa: Accounting for Variability in Farm Management Practices. Agronomy 2019, 9, 639. [CrossRef]

8. Amouzou, K.A.; Lamers, J.P.A.; Naab, J.B.; Borgemeister, C.; Vlek, P.L.G.; Becker, M. Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. Field Crops Res. 2019, 235, 104–117. [CrossRef]

9. Amouzou, K.A.; Naab, J.B.; Lamers, J.P.A.; Borgemeister, C.; Becker, M.; Vlek, P.L.G. CROP-GRO-Cotton model for determining climate change impacts on yield, water- and N- use efficiencies of cotton in the Dry Savanna of West Africa. Agric. Syst. 2018, 165, 85–96. [CrossRef]

10. Danso, I.; Webber, H.; Bourgault, M.; Ewert, F.; Naab, J.B.; Gaiser, T. Crop management adaptations to improve and stabilize crop yields under low-yielding conditions in the Sudan Savanna of West Africa. Eur. J. Agron. 2018, 101, 1–9. [CrossRef]

11. Nafi, E.; Webber, H.; Danso, I.; Naab, J.B.; Frei, M.; Gaiser, T. Interactive effects of conservation tillage, residue management, and nitrogen fertilizer application on soil properties under maize-cotton rotation system on highly weathered soils of West Africa. Soil Tillage Res. 2020, 196, 104473. [CrossRef]

12. Demeke, M.; Di Marcantonio, F.; Morales-Opazo, C. Understanding the performance of food production in sub-Saharan Africa and its implications for food security. J. Dev. Agric. Econ. 2013, 5, 425–443. [CrossRef]

13. Showers, K.B. Europe’s long history of extracting African renewable energy: Contexts for African scientists, technologists, innovators and policy-makers. Afr. J. Sci. Technol. Innov. Dev. 2014, 6, 301–313. [CrossRef]

14. Sylla, N.S. From a marginalised to an emerging Africa? A critical analysis. Rev. Afr. Political Econ. 2014, 41, S7–S25. [CrossRef]

15. Adaawen, S. Understanding Climate Change and Drought Perceptions, Impact and Responses in the Rural Savannah, West Africa. Atmosphere 2021, 12, 594. [CrossRef]

16. Ibrahim, Y.Z.; Balzter, H.; Kaduk, J. Land degradation continues despite greening in the Nigeria-Niger border region. Glob. Ecol. Conserv. 2018, 16, e00505. [CrossRef]

17. Jayne, T.S.; Sanchez, P.A. Agricultural productivity must improve in sub-Saharan Africa. Science 2021, 372, 1045–1047. [CrossRef]

18. DeFries, R.; Mondal, P.; Singh, D.; Agrawal, I.; Fanzo, J.; Remans, R.; Wood, S. Synergies and trade-offs for sustainable agriculture: Nutritional yields and climate-resilience for cereal crops in Central India. Glob. Food Secur. 2016, 11, 44–53. [CrossRef]

19. Ayamga, E.A.; Kemausuor, F.; Addo, A. Technical analysis of crop residue biomass energy in an agricultural region of Ghana. Resour. Conserv. Recycl. 2015, 96, 51–60. [CrossRef]
20. Kragt, M.E.; Robertson, M.J. Quantifying ecosystem services trade-offs from agricultural practices. *Ecol. Econ.* 2014, 102, 147–157. [CrossRef]

21. Mohanty, M.; Sinha, N.K.; Somasundaram, J.; Mc Dermid, S.S.; Patra, A.K.; Singh, M.; Dwivedi, A.K.; Reddy, K.S.; Rao, C.S.; Prabhakar, M.; et al. Soil carbon sequestration potential in a Vertisol in central India- results from a 43-year long-term experiment and APSIM modeling. *Agric. Syst.* 2020, 184, 102906. [CrossRef]

22. O’Leary, G.J.; Liu, D.L.; Ma, Y.; Li, F.Y.; McCaskill, M.; Conyers, M.; Dalal, R.; Reeves, S.; Page, K.; Dang, Y.P.; et al. Modelling soil organic carbon 1. Performance of APSIM crop and pasture modules against long-term experimental data. *Geoderma* 2016, 264, 227–237. [CrossRef]

23. Akineseye, F.M.; Adam, M.; Agele, S.O.; Hoffmann, M.P.; Traore, P.C.S.; Whitbread, A.M. Assessing crop model improvements through comparison of sorghum (*Sorghum bicolor* L. moench) simulation models: A case study of West African varieties. *Field Crops Res.* 2017, 201, 19–31. [CrossRef]

24. Akponikpe, P.B.I. Millet Response to Water and Soil Fertility Management in the Sahelian Niger: Experiments and Modelling. Ph.D. Thesis, Université Catholique de Louvain, Louvain-la-Neuve, Belgium, 2008.

25. Tachie-Obeng, E.; Akponikpe, P.B.I.; Adiku, S. Considering effective adaptation options to impacts of climate change for maize production in Ghana. *Environ. Dev.* 2013, 5, 131–145. [CrossRef]

26. Kpong or, D. Spatially Explicit Modeling of Sorghum (*Sorghum bicolor* (L.) Moench) Production in a Complex Terrain in a Semi-arid Region of Ghana. Ph.D. Thesis, University of Bonn, Bonn, Germany, 2007.

27. Amarasingha, R.P.R.K.; Suriyagoda, L.D.B.; Marambe, B.; Gaydon, D.S.; Galagedara, L.W.; Punyawardena, R.; Silva, G.L.L.P.; Nidumolu, U.; Howden, M. Simulation of crop and water productivity for rice (*Oryza sativa* L.) using APSIM under diverse agro-climatic conditions and water management strategies in Sri Lanka. *Agric. Water Manag.* 2015, 160, 132–143. [CrossRef]

28. Hoffmann, M.P.; Odhiambo, J.J.O.; Koch, M.; Ayisi, K.K.; Zhao, G.; Soler, A.S.; Rötter, R.P. Exploring adaptations of groundnut cropping to prevailing climate variability and extremes in Limpopo Province, South Africa. *Field Crops Res.* 2018, 219, 1–13. [CrossRef]

29. Faye, B.; Webber, H.; Naab, J.B.; MacCarthy, D.S.; Adam, M.; Ewert, F.; Lamers, J.P.A.; Schleussner, C.-F.; Ruane, A.; Gessner, U.; et al. Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna. *Environ. Res. Lett.* 2018, 13, 34014. [CrossRef]

30. MacCarthy, D.S.; Adam, M.; Fredua h, B.S.; Fosu-Mensah, B.Y.; Ampim, P.A.Y.; Iy, M.; Traore, P.S.; Adiku, S.G.K. Climate Impact and Variability on Cereal Productivity among Smallholder Farmers under Future Production Systems in West Africa. *Sustainability* 2021, 13, 5191. [CrossRef]

31. La Notte, A.; D’Amato, D.; Mäkinen, H.; Paracchini, M.L.; Lique, C.; Ego h, B.; Geneletti, D.; Crossman, N.D. Ecosystem services classification: A systems ecology perspective of the cascade framework. *Ecol. Indic.* 2017, 74, 392–402. [CrossRef]

32. Gaydon, D.S.; Balwinder-Singh; Wang, E.; Poulton, P.L.; Ahmad, B.; Ahmed, F.; Akhter, S.; Ali, I.; Amarasingha, R.; Chaki, A.K.; et al. Evaluation of the APSIM model in cropping systems of Asia. *Field Crops Res.* 2017, 204, 52–75. [CrossRef]

33. Ritchie, J.T. A user-oriented model of the soil water balance in wheat. In *Wheat Growth and Modelling*; Day, W., Atkin, R.K., Eds.; Springer: Boston, MA, USA, 1985; pp. 293–305. ISBN 148993667X.

34. Probert, M.E.; Dimes, J.P.; Keating, B.A.; Dalal, R.C.; Strong, W.M. APSIM’s water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agric. Syst.* 1998, 56, 1–28. [CrossRef]

35. *Methodology in Soil Water and Solute Balance Modelling: An Evaluation of the APSIM-SoilWat and SWATm2 Models: Report of an APSRI/CSIRO Division of Soils Workshop Held in Brisbane, Australia, 16–18 May 1995*; Verburg, K., Ed.; CSIRO Division of Soils: Canberra, Australia, 1996; ISBN 0-643-05868-0.

36. Keating, B.A.; Carberry, P.S.; Hammer, G.L.; Probert, M.; Robert son, M.J.; Holzworth, D.; Huth, N.I.; Hargreaves, J.N.G.; Meinke, H.; Hochman, Z.; et al. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.* 2003, 18, 267–288. [CrossRef]

37. MacCarthy, D.S.; Vlek, P.L.G.; Bat i ono, A.; Tabo, R.; Fosu, M. Modeling nutrient and water productivity of sorghum in smallholder farming systems in a semi-arid region of Ghana. *Field Crops Res.* 2010, 118, 251–258. [CrossRef]

38. Buri, M.M.; Ishida, F.; Kubota, D.; Masunaga, T.; Nakatsuki, T. Soils of flood plains of West Africa: General fertility status. *Plant Nutr.* 1999, 56, 1–35. [CrossRef]

39. MacCarthy, D.S.; Vlek, P.L.G.; Bat i ono, A.; Tabo, R.; Fosu, M. Modeling nutrient and water productivity of sorghum in smallholder farming systems in a semi-arid region of Ghana. *Field Crops Res.* 2010, 118, 251–258. [CrossRef]

40. Buri, M.M.; Ishida, F.; Kubota, D.; Masunaga, T.; Nakatsuki, T. Soils of flood plains of West Africa: General fertility status. *Plant Nutr.* 1999, 56, 1–35. [CrossRef]

41. Buri, M.M.; Ishida, F.; Kubota, D.; Masunaga, T.; Nakatsuki, T. Soils of flood plains of West Africa: General fertility status. *Plant Nutr.* 1999, 56, 1–35. [CrossRef]

42. Duku, M.H.; Gu, S.; Hagan, E.B. A comprehensive review of biomass resources and biofuels potential in Ghana. *Renew. Sustain. Energy Rev.* 2011, 15, 404–415. [CrossRef]

43. Amole, T.A.; Ayantunde, A.A. Improving livestock productivity: Assessment of feed resources and livestock management practices in Sudan-Savanna zones of West Africa. *Afr. J. Agric. Res.* 2016, 11, 422–440. [CrossRef]
45. Amole, T.A.; Ayantunde, A.A. Assessment of Existing and Potential Feed Resources for Improving Livestock Productivity in Niger. *Int. J. Agric. Res.* 2016, 11, 40–55. [CrossRef]

46. Investing.com. USD/GHS—US Dollar Ghanaian Cedi. Available online: https://uk.investing.com/currencies/USD-GHS-historical-data (accessed on 29 July 2021).

47. United Nations University; World Health Organization; Food and Agriculture Organization of the United Nations. *Human Energy Requirements: Report of a Joint FAO/WHO/UNU Expert Consultation*; Rome, 17–24 October 2001; United Nations University: Rome, Italy, 2004; ISBN 92-5-105212-3.

48. World Health Organization; Food and Agriculture Organization of the United Nations. *Vitamin and Mineral Requirements in Human Nutrition: [Report of a joint FAO/WHO Expert Consultation, Bangkok, Thailand, 21–30 September 1998/World Health Organization and Food and Agriculture Organization of the United Nations.]*, 2nd ed.; World Health Organization: Geneva, Switzerland, 2004; ISBN 92-4-154612-3.

49. GSS. *Population & Housing Census 2010: District Analytical Report*; Bolgatanga Municipality: Accra, Ghana, 2014. Available online: https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Upper%20East/Bolga.pdf (accessed on 6 August 2021).

50. GSS. *Population & Housing Census 2010: District Analytical Report*; Bongo: Accra, Ghana, 2014. Available online: https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Upper%20East/Bongo.pdf (accessed on 6 August 2021).

51. Barthès, B.G.; Penche, A.; Hien, E.; Deleporte, P.; Clermont-Dauphin, C.; Cournac, L.; Manlay, R.J. Effect of ramial wood amendment on sorghum production and topsoil quality in a Sudano-Sahelian ecosystem (central Burkina Faso). *Agrofor. Syst.* 2015, 89, 81–93. [CrossRef]

52. Ouattara, D. *Sorghum Grain Yield and Nutrient Dynamics under Varying Rates of Fertilizer Application in the Sub-Saharan Zone of Burkina Faso*. Master’s Thesis, KNUST, Kumasi, Ghana, 2015.

53. Shuaibu, Y.M.; Garba, A.A.; Voncir, N. Influence of legume residue and nitrogen fertilizer on the growth and yield of sorghum (*Sorghum bicolor* (L.) Moench) in Bauchi State, Nigeria. *AFFAND* 2015, 15, 10600–10075.

54. Akinessye, F.M.; Ajege, H.A.; Kamara, A.Y.; Adefisan, E.A.; Whitbread, A.M. Understanding the response of sorghum cultivars to nitrogen applications in the semi-arid Nigeria using the agricultural production systems simulator. *J. Plant Nutr.* 2020, 43, 834–850. [CrossRef]

55. Ba, T.; Yamoah, C.F.; Diangar, S. An appraisal of irrigated temperate and tropical millet varieties in the semiarid region of Senegal. *Afr. Crop Sci. J.* 2000, 8. [CrossRef]

56. Bayala, J.; Teklehaimanot, Z.; Ouedraogo, S.J. Millet production under pruned tree crowns in a parkland system in Burkina Faso. *Agron. Sustain. Dev.* 2006, 54, 203–214. [CrossRef]

57. Diangar, S.; Fofana, A.; Diagne, M.; Yamoah, C.F.; Dick, R.P. Pearl millet-based intercropping systems in the semiarid areas of Senegal. *Afr. Crop. Sci. J.* 2004, 12. [CrossRef]

58. Naab, J.B.; Koo, J.; Traore, P.C.S.; Adiku, S.G.K.; Jones, J.W.; Boote, K.J.; Carbon Enhancing Systems (CEMS). *Estimation of Soil Carbon Sequestration Potential in Small-Holder Farming Systems in Northern Ghana*; SM CRSP Bulletin: Ithaca, NY, USA, 2008; Available online: https://vtechworks.lib.vt.edu/handle/10919/69022 (accessed on 29 June 2020).

59. Oluwasemire, K.O.; Stigter, C.J.; Owonubi, J.J.; Jagtap, S.S. Seasonal water use and water productivity of millet-based cropping systems in the Nigerian Sudan savanna near Kano. *Agric. Water Manag.* 2002, 56, 207–227. [CrossRef]

60. Sanou, J.; Bayala, J.; Teklehaimanot, Z.; Bazié, P. Effect of shading by baobab (*Adansonia digitata*) and néré (*Parkia biglobosa*) on yields of millet (*Pennisetum glaucum*) and taro (*Colocasia esculenta*) in parkland systems in Burkina Faso, West Africa. *Agron. Sustain. Dev.* 2015, 35, 431–441. [CrossRef]

61. Traore, B.; Descheemaeker, K.; van Wijk, M.T.; Corbeels, M.; Supit, I.; Giller, K.E. Modelling cereal crops to assess future climate risk for family food self-sufficiency in southern Mali. *Field Crops Res.* 2017, 201, 133–145. [CrossRef]

62. Zakaria, M. *Evaluation of Five Promising Pearl Millet Lines to Insect Pests in Upper East Region*. Master’s Thesis, KNUST, Kumasi, Ghana, 2016.

63. Shiyan, J.O. Growth and yield response of groundnut (*Arachis hypogaea* L.) to plant densities and phosphorus on an ultisol in Southeastern Nigeria. *Libyan Agric. Res. Cent. J.* 2010, 1, 211–214.

64. Aboyeji, C.; Dunsin, O.; Adegbe, O.A.; Chinedum, C.; Suleman, K.O.; Okunola, F.O.; Wulabi, O.O.; Olofinoye, T.A.J. Zinc Sulphate and Boron-Based Foliar Fertilizer Effect on Growth, Yield, Minerals, and Heavy Metal Composition of Groundnut (*Arachis hypogaea* L.) Grown on an Alfisol. *Int. J. Agron.* 2019, 2019, 1–7. [CrossRef]

65. Ileodun, O.C.; Harira, S.; Tanko, M.U. Sustainable crop production: Growth and yield response of three varieties of groundnut (*Arachis hypogaea* L.) grown on an Alfisol. *Int. J. Agron.* 2019, 56, 10060–10075.

66. Lumb, G.; Singh, L.; Yayock, J.Y. A decade of fertilizer research on groundnuts (*Arachis hypogaea* L.) in the savannah zone of Nigeria. *Nutr. Cycl. Agroecosyst.* 1995, 6, 157–170. [CrossRef]

67. Naab, J.B.; Singh, P.; Boote, K.J.; Jones, J.W.; Marfo, K.O. Using the CROPGRO-Peanut Model to Quantify Yield Gaps of Peanut in the Guinean Savannah Zone of Ghana. *Agron. J.* 2004, 96, 1231–1242. [CrossRef]
69. Naab, J.B.; Seini, S.S.; Gyasi, K.O.; Mahama, G.Y.; Prasad, P.V.V.; Boote, K.J.; Jones, J.W. Groundnut yield response and economic benefits of fungicide and phosphorus application in farmer-managed trials in Northern Ghana. *Ex. Agric.* **2009**, *45*, 385–399. [CrossRef]

70. Akumaga, U.; Tarhule, A.; Yusuf, A.A. Validation and testing of the FAO AquaCrop model under different levels of nitrogen fertilizer on rainfed maize in Nigeria, West Africa. *Agric. For. Meteorol.* **2017**, *232*, 225–234. [CrossRef]

71. Igwé, M.A.; Oga, A.C.; Saidou, A.; Balogoun, I.; Anago, F.; Ezui, G.; Youl, S.; Kpágbin, G.; Mando, A.; Sogbedji, J. Updating fertilizer formulation for maize cultivation (*Zea mays* L.) on Ferric Luvisols and Gleysols in the municipality of Tanguíetía, North-West Benin. *Glob. Adv. Agric. Res. J. Agric. Sci.* **2015**, *4*, 858–863.

72. Srivastava, A.K.; Mboh, C.M.; Gaiser, T.; Ewert, F. Impact of climatic variables on the spatial and temporal variability of crop yield and biomass gap in Sub-Saharan Africa—A case study in Central Ghana. *Field Crops Res.* **2017**, *203*, 33–46. [CrossRef]

73. Abaida, R.C.; Okogun, J.A.; Kolawole, G.O.; Diels, J.; Randall, P.; Sanginga, N. Evaluation of cowpea genotypes for variations in their contribution of N and P to subsequent maize crop in three agro-ecological zones of West Africa. In *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*; Batiano, A., Waswa, B., Kihara, J., Kimetu, J., Eds.; Springer: Dordrecht, The Netherlands, 2007; pp. 401–412. ISBN 978-1-4020-5759-5.

74. Buah, S.S.J.; Abatania, L.N.; Aflakpui, G.K.S. Quality Protein Maize Response to Nitrogen Rate and Plant Density in the Guinea Savanna Zone of Ghana. *West Afr. J. Appl. Ecol.* **2010**, *16*. [CrossRef]

75. Danso, I.; Gaiser, T.; Webber, H.; Naab, J.; Ewert, F. Response of Maize to Different Nitrogen Application Rates and Tillage Practices Under Two Slope Positions in the Face of Current Climate Variability in the Sudan Savanna of West Africa. In *Strategies for Building Resilience against Climate and Ecosystem Changes in Sub-Saharan Africa*; Saito, O., Kranjac-Berisavljevic, G., Takeuchi, K.A., Gyasi, E., Eds.; Springer: Singapore, 2018; pp. 41–58. ISBN 978-981-10-4796-1.

76. Kombiok, J.M.; Safo, E.Y.; Quansah, C. Yield and Nitrogen fixation of cowpea as affected by tillage and cropping systems in the Northern Savanna zone of Ghana. *West Afr. J. Appl. Ecol.* **2005**, *7*, 95–108. [CrossRef]

77. Yusuf, A.A.; Abaida, R.C.; Iwuafor, E.N.O.; Olufajo, O.O.; Sanginga, N. Rotation effects of grain legumes and fallow on maize yield, microbial biomass and chemical properties of an Alfisol in the Nigerian savanna. *Agric. Ecosyst. Environ.* **2009**, *129*, 325–331. [CrossRef]

78. Niang, A.; Becker, M.; Ewert, F.; Dieng, I.; Gaiser, T.; Tanaka, A.; Senthilkumar, K.; Rodenburg, J.; Johnson, J.-M.; Akakpo, C.; et al. Variability and determinants of yields in rice production systems of West Africa. *Field Crops Res.* **2017**, *207*, 1–12. [CrossRef]

79. Tanaka, A.; Johnson, J.-M.; Senthilkumar, K.; Akakpo, C.; Segda, Z.; Yameogo, L.P.; Bassoro, I.; Lamare, D.M.; Allarangaye, M.D.; Gbakatchete, H.; et al. On-farm rice yield and its association with biophysical factors in sub-Saharan Africa. *Eur. J. Agron.* **2017**, *85*, 1–11. [CrossRef]

80. Inusah, B.I.Y.; Dogbe, W.; Abdulai, A.L.; Yirzagla, J.; Mawunya, M.; Issahak, A.S. Yield Gap Survey in Sudanno-Guinea Savanna Agro-Ecological Zones of Ghana. *SAR* **2014**, *4*, 127. [CrossRef]

81. Oteng-Darko, P.; Kyei-Baffour, N.; Ofori, E. Simulating rice yields under climate change scenarios using the CERES-Rice model. *Afr. Crop Sci. J.* **2012**, *20*, 401–408.

82. Idriss, S.; Mohamed, D.; Korodjouma, O.; Baba, S.; Charles, W. Rainfed rice response to fertilizer in the Sudan Savanna of West Africa. *Afr. J. Agric. Res.* **2018**, *13*, 1033–1041. [CrossRef]

83. Kone, B.; Sylvester, O.; Diatta, S.; Somado, E.; Valere, K.; Sahrawat, K.L. Response of interspecific and sativa upland rices to Mali phosphate rock and soluble phosphate fertilizer. *Arch. Agron. Soil Sci.* **2011**, *57*, 421–434. [CrossRef]

84. Bedada, W.; Lemenih, M.; Karlton, E. Soil nutrient build-up, input interaction effects and plot level N and P balances under long-term addition of compost and NP fertilizer. *Agric. Ecosyst. Environ.* **2016**, *218*, 220–231. [CrossRef]

85. Wortmann, C.S.; Kaizzi, C.K. Nutrient balances and expected effects of alternative practices in farming systems of Uganda. *Agric. Ecosyst. Environ.* **2019**, *138*, 115–129. [CrossRef]

86. Harris, F.M.A. Farm-level assessment of the nutrient balance in northern Nigeria. *Agric. Ecosyst. Environ.* **1998**, *71*, 201–214. [CrossRef]

87. Krupnik, T.J.; Shennan, C.; Rodenburg, J. Yield, water productivity and nutrient balances under the System of Rice Intensification and Recommended Crops Management. *Afr. J. Agric. Res.* **2013**, *8*, 150–156. [CrossRef]

88. Saidou, A.; Janssen, B.H.; Temminghoff, E.J.M. Effects of soil properties, mulch and NPK fertilizer on maize yields and nutrient budgets on ferralitic soils in southern Benin. *Agric. Ecosyst. Environ.* **2003**, *100*, 265–273. [CrossRef]

89. Pasley, H.R.; Camberato, J.J.; Cairns, J.E.; Zaman-Allah, M.; Das, B.; Vyn, T.J. Nitrogen rate impacts on tropical maize nitrogen use efficiency and soil nitrogen depletion in eastern and southern Africa. *Nutr. Cycl. Agroecosyst.* **2020**, *116*, 397–408. [CrossRef] [PubMed]

90. Mujuru, L.; Rusinamhodzi, L.; Nyamangara, J.; Hoosbeek, M.R. Effects of nitrogen fertilizer and manure application on storage of carbon and nitrogen under continuous maize cropping in Arenosols and Luvisols of Zimbabwe. *J. Agric. Sci.* **2016**, *154*, 242–257. [CrossRef]

91. Bado, B.V.; Whitbread, A.; Sanoussi Manzo, M.L. Improving agricultural productivity using agroforestry systems: Performance of millet, cowpea, and ziziphus-based cropping systems in West Africa Sahel. *Agric. Ecosyst. Environ.* **2021**, *305*, 107175. [CrossRef]

92. Zougmore, R.; Mando, A.; Stroosnijder, L.; Guillobez, S. Nitrogen flows and balances as affected by water and nutrient management in a sorghum cropping system of semi-arid Burkina Faso. *Field Crops Res.* **2004**, *90*, 235–244. [CrossRef]
120. Assefa, B.T.; Chamberlin, J.; Reidsma, P.; Silva, J.V.; van Ittersum, M.K. Unravelling the variability and causes of smallholder maize yield gaps in Ethiopia. *Food Secur.* **2020**, *12*, 83–103. [CrossRef]

121. Müller, C.; Elliott, J.; Pugh, T.A.M.; Ruane, A.C.; Ciais, P.; Balkovic, J.; Deryng, D.; Folberth, C.; Izaurralde, R.C.; Jones, C.D.; et al. Global patterns of crop yield stability under additional nutrient and water inputs. *PLoS ONE* **2018**, *13*, e0198748. [CrossRef]

122. Falconnier, G.N.; Corbeels, M.; Boote, K.J.; Affholder, F.; Adam, M.; MacCarthy, D.S.; Ruane, A.C.; Nendel, C.; Whitbread, A.M.; Justes, É.; et al. Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. *Glob. Chang. Biol.* **2020**, [CrossRef] [PubMed]

123. Chapman, S.; Birch, C.E.; Pope, E.; Sallu, S.; Bradshaw, C.; Davie, J.; Marsham, J.H. Impact of climate change on crop suitability in sub-Saharan Africa in parameterized and convection-permitting regional climate models. *Environ. Res. Lett.* **2020**, *15*, 94086. [CrossRef]

124. Akanvou, R.K. Quantitative Understanding of the Performance of Upland Rice-Cover Legume Cropping Systems in West Africa. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 2001.