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Key Points:

- Intercropping alongside sufficient residue return allows for stabilizing long-term yields
- Intercropping allows to maintain SOC stocks in low or zero fertilizer systems if all residues are returned to the soil
- Intercropping reduces the amount of N fertilizer needed to maintain soil N stocks

Supporting Information:

Supporting Information may be found in the online version of this article.

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Intercropping Legumes Improves Long Term Productivity and Soil Carbon and Nitrogen Stocks in Sub-Saharan Africa

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Abstract Food, feed, and fiber production needs to increase to support demands of the growing population in Sub-Saharan Africa (SSA), while soil fertility continues to decline. Intercropping, the cultivation of two or more crop species on the same field, can provide yield benefits and is suggested to positively affect soil organic carbon (C) and nitrogen (N) stocks. This study uses the biogeochemical model system LandscapeDNDC with the objective to (a) represent maize-legume intercropping systems in different bioregions in SSA by simultaneously simulating both crops and their interactions and (b) assess long-term (20 years) impacts of intercropping under varying mineral fertilizer inputs (0–150 kg N ha^{-1} yr^{-1}) on productivity as well as soil organic C and N stocks. We test LandscapeDNDC on 82 field data sets (site-year-treatment combinations) from 18 sites to represent yields and soil C/N dynamics of maize-legume intercropping systems. Using the model for long-term scenario simulations showed that intercropping allows to sustain productivity and to improve or maintain SOC stock in low or zero fertilizer systems if all residues are returned to the soil. In contrast, for sole-cropped maize systems, a decline in SOC stocks was simulated unless a minimum of 35 kg N ha^{-1} yr^{-1} of fertilizer was applied at full residue return. We conclude that intercropping using legumes alongside sufficient residue return allows for stabilizing long-term yields while avoiding SOC losses even with low fertilizer N inputs. Overall, our study confirms the potential of intercropping as a sustainable agricultural practice that could significantly contribute to food security in SSA.

1. Introduction

The need for more food, feed, and fiber to support a growing population is putting pressure on land in Sub-Saharan Africa (SSA). Soil nutrient mining is one of the most important drivers for soil degradation, inducing reduced crop productivity, lower plant biomass and reduced soil cover, which subsequently exacerbate erosion, acidification and hard pan formation (Sheldrick et al., 2002; Smaling et al., 1997; B. Vanlauwe et al., 2015). Intercropping, the simultaneous cultivation of two or more crop species on the same piece of land, is important in many subsistence or low-input agricultural systems in SSA (Namatsheve et al., 2020; Ngwira et al., 2012). Intercropping can have multiple benefits such as greater yield stability and resource use efficiency compared with sole cropping systems (Brooker et al., 2015; Li et al., 2021; Raseduzzaman & Jensen, 2017). Yield benefits of intercrops are observed in terms of land equivalent ratio (LER), that is, intercrop systems require on average 19% less land compared with production of the same yields in sole crop systems, and produce 1.5 *t* ha^{-1} grain yield more than expected on the basis of the sole crop yields in a global meta-analysis (Li et al., 2020). While yield benefits of intercrops are evident if diversified production and protein production are targeted, grain or calorie yield production was slightly reduced compared with the *most productive* sole crop based on the same global data set (Li et al., 2023). Intercropping has further been shown to sustain and even improve soil quality, reducing weed growth and risks due to pests and diseases (Brooker et al., 2015; Himmelstein et al., 2017; Li et al., 2021; Rusinamhodzi et al., 2012). Generally, intercropping systems are discussed as cornerstone practice to achieve sustainable intensification of low input systems or as a promising option to reduce environmental impacts and land use as compared to sole cropping systems (Kuyah et al., 2021). Nevertheless, there are several barriers to adoption such as increased labor requirements decreased caloric yield of focal crop and increased complexity of management (Bedoussac et al., 2015).

Higher productivity of intercrops with respect to sole crops can be attributed to the complementary use of resources for plant growth (Ofori & Stern, 1987; Willey, 1990). The intercrop species show spatial and/or temporal

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differences in access to light, water and nutrients, known as niche complementarity. Inter-species competition, due to niche complementarity, restricts the co-existing plants less in their development than intra-species competition, resulting in increased resource use. Temporal complementary effects occur when resource demands are asynchronous due to differences in plant development between cultivated species. Spatial effects include complementary resource use for light due to differences in canopy structure, and for water and nutrients due to differences in root architecture (Willey, 1990).

In cereal-legume intercropping systems, the symbiotic N fixation associated with legumes enables complementary resource use with respect to nitrogen (N). Maize relies on N acquisition from soil stocks or external N inputs in the form of synthetic or organic fertilizers, whereas legumes promote atmospheric N_2-fixation by symbiotic bacteria (*Rhizobium* and *Bradyrhizobium*) and use fixed N for its own metabolism and growth. As a secondary effect, if incorporated or left on the soil, legume residues with their comparable narrow C/N ratios can improve soil fertility and increase plant N availability via mineralization (Giller, 2001), which becomes evident when legumes are grown in rotation with cereals (Franke et al., 2018).

Until now, smallholder farmers in SSA commonly grow cereal crops such as maize (*Zea mays L.*) in continuous monoculture (Baudron et al., 2012). Organic and mineral fertilizer application rates are typically low due to the high cost of mineral fertilizers (Ngwira et al., 2012) and their limited availability (Njoroge et al., 2023), leading to the mining of the soil N pool (Hickman et al., 2020; Zhou et al., 2014). This in combination with low return rates of crop residues, and an unreliable rainfall regime imposes high risks of crop failure, which can be alleviated by legume-supported intercropping systems. Such systems have been found to show higher soil organic carbon and nitrogen levels, supporting nutrient supply (Cong et al., 2015; Li et al., 2021) and water retention (Kermah et al., 2017). The use of legumes as intercrops in cereal-based systems can provide additional N inputs if only low or moderate mineral N fertilizer rates are applied (Myaka et al., 2006; Namatsheve et al., 2020; Snapp et al., 2002, 2018; Stagnari et al., 2017). The five main grain legume crops already used as intercrops in SSA are groundnut (17.55 Mha), cowpea (15.07 Mha), common bean (8.67 Mha), soybean (2.94 Mha) and pigeon pea (0.63 Mha), which together cover 92% of the total grain legume production area (FAOSTAT, 2020).There are regional differences in adoption, for example, most groundnut, cowpea and soybean cultivation is located in Western Africa, while most common bean and pigeon pea cultivation areas are located in Eastern Africa (FAOSTAT, 2020).

To improve our understanding of the impact of intercropping on yields, C and N cycling and associated losses to the environment, in addition to measurements, we can use current knowledge to set up and inform ecosystem models in order to test whether we can realistically simulate these diversified cropping systems. Several biogeochemical models implemented intercropping and tested it at the field scale. For instance, the intercropping version of APSIM (Carberry et al., 1996; Keating et al., 2003) and STICS were shown to reproduce productivity and resource use of intercropping systems (Brisson et al., 2004; Chimonyo et al., 2016; Corre-Hellou et al., 2009; Knörzer, Grözinger, et al., 2011; Knörzer, Lawes, et al., 2011). All these models, including LandscapeDNDC, use the assumption of horizontal homogeneity (concept of a 1-D column). Previous studies were conducted with the goal of comparing the effects of different intercropping system designs and management options on yields at the site scale. However, modeling studies have not yet aimed at evaluating the effects of intercropping on soil N cycling and at generalized (i.e., multi-site) parametrizations suitable also for spatial upscaling procedures. In this study, we aim to represent yields and plant biomass under different climatic and soil conditions and beyond that validate the N fluxes introduced by intercropping, namely crop N uptake and N_2 fixation by legumes, which have been neglected in almost all previous studies (Corre-Hellou et al., 2009 is the exception, but limited to one site). Based on this validation, we can assess the impact of soil N cycling on environmental losses, soil N stock changes and corresponding soil fertility.

Due to the particular importance of intercropping in low input systems in SSA, within this study we explicitly assess long-term decadal effects of intercropping on yields and C and N cycling, which are often not considered in field studies. To this end, we calibrate and validate the LandscapeDNDC model system on biomass production (crop yield, aboveground biomass), leaf area index (LAI), plant N uptake and biological N_2 fixation (BNF) via legumes for the most important intercropping systems of SSA. Based on this comprehensive validation, we evaluate the long-term effects of intercropping on soil C and N stock changes and yields in different bioregions of SSA.

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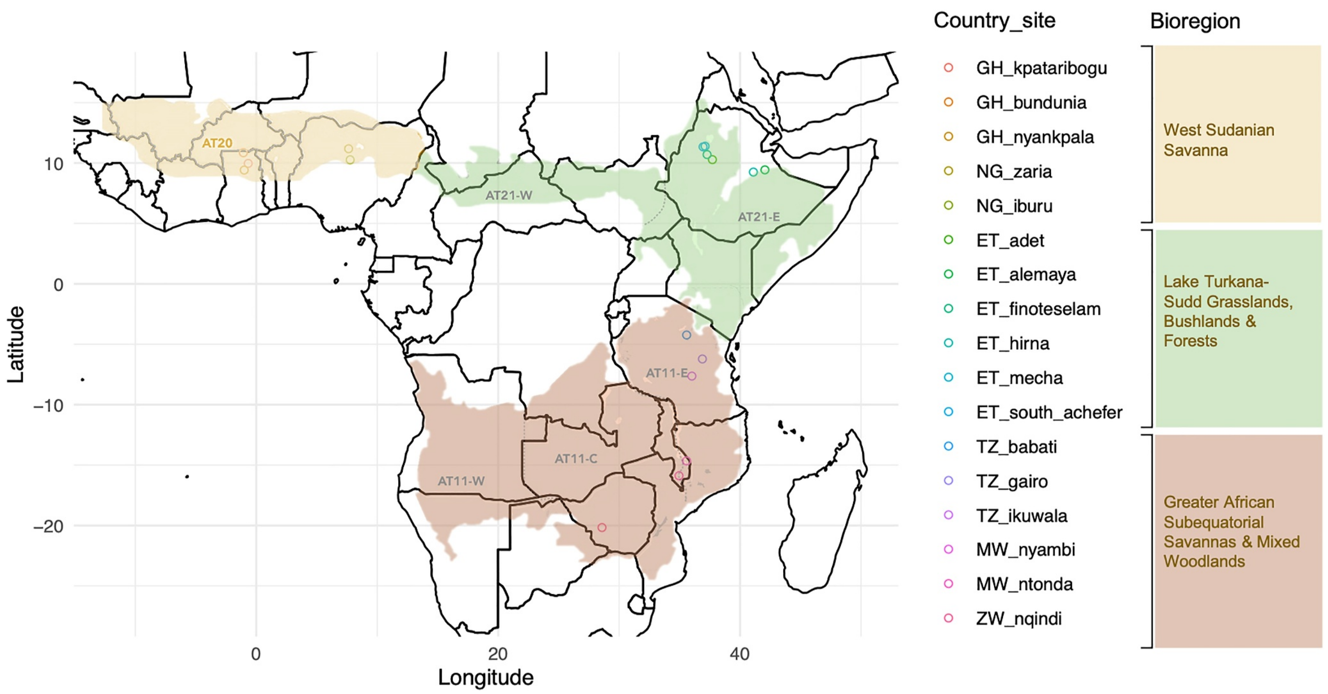

Figure 1. Map showing the study sites and respective bioregions in the Afrotropic (AT) (https://www.oneearth.org/bioregions-2020/). Bioregions consist of several ecozones after (Olson et al., 2001) (See also https://www.oneearth.org/navigator/). For each crop in each bioregion, we determined a representative species parameterization (see Section 2.6).

2. Materials and Methods

2.1. Site Data Selection

We conducted a literature search on maize-based intercropping systems, which are the most common in SSA. We used the combination of the keywords "intercrop*," "maize," "SSA" and selected observation data from publications where site data were provided in a sufficiently detailed manner regarding information on the experimental setup, site management and soil and where besides intercropped treatments also measurements of sole crop treatments were reported. One exception here was pigeon pea, where sole crop treatments were not reported. The search was extended by screening the references of relevant publications. Overall, the literature search resulted in a total of 82 data sets (site-year-treatment combinations) from 18 sites in seven countries, which represented the variety of climatic and soil conditions in SSA (Figure 1, Table 1).

Focus target variables for model calibration and validation were aboveground plant biomass, grain yield, N in plant biomass, LAI as well as biological N_2 fixation by legumes. The combinations of interest were maize intercropped with cowpea (*Vigna unguiculata L. Walp.*), soybean (*Glycine max L. Mer.*), peanut (*Arachis hypogea L.*), common bean (*Phaseolus vulgaris L.*) and pigeon pea (*Cajanus Cajan L. Millsp.*). Further, we aimed to cover a variety of different soils and climatic conditions. We restricted our analysis to intercrops being sown at the same time, excluding relay intercropping. Grain yields were adjusted to dry weight according to the grain moisture content given in the respective studies. The collected site data were separated into calibration and independent validation data sets. When a study presented measurements from two or more sites, half of the sites were used for calibration and the other half for validation.

2.2. Site Description and Characteristics

The sites were located in three different bioregions across the largest of SSA's maize growing areas (Figure 1). Five sites were located in the West Sudanian Savanna Bioregion (AT20) in Ghana and Nigeria. These sites were characterized by mean annual temperatures ranging between 25 and 32°C and annual precipitation ranging between 500 and 1,200 mm, and the soil types Plinthosol, Luvisol, Acrisol and Umbrisol (Table 1) (Kamara et al., 2019; Kermah et al., 2018; Kombiok et al., 2006). Six high altitude sites (1,870 up to 2,240 m asl) were

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Table 1
Site Information and References for Calibration and Validation Sites

Coordinates	Site	Country	Ecozone	Height asl (m)	MA T (°C)	MA P (mm)	Soil type	Intercrops	Reference
9°58′ N, 0° 40′ W	GH_kpataribogu	Ghana	West Sudanian savanna	172	29	598	Plinthosol	cowpea, soybean, peanut	Kermah et al. (2018)
10°51′ N, 1° 04′ W	GH_bundunia	Ghana	West Sudanian savanna	185	29	532	Plinthosol	cowpea, soybean, peanut	Kermah et al. (2018)
9°25′ N, 1° 00′ W	GH_nyankpala	Ghana	West Sudanian savanna	183	32	800–1,000	Ferric Luvisol	cowpea	Kombiok et al. (2006)
11°11′ N, 7° 38′ E	NG_zaria	Nigeria	West Sudanian savanna	580	25	911–941	Chromic Acrisol	soybean	Kamara et al. (2019)
10°16′ N, 7° 46′ E	NG_iburu	Nigeria	West Sudanian savanna	650	25	1,071–1,285	Cambic Umbrisol	soybean	Kamara et al. (2019)
11°23′ N, 37°06′E	ET_mecha	Ethiopia	Ethiopian montane grasslands and woodlands	1,982	20	2,150	Nitisol	common bean	Alemayehu et al. (2017)
11°20′N, 36° 56′ E	ET_south_achefer	Ethiopia	Ethiopian montane grasslands and woodlands	2,021	18	2,050	Nitisol	common bean	Alemayehu et al. (2017)
11°17′ N, 37° 43′ E	ET_adet	Ethiopia	Ethiopian montane grasslands and woodlands	2,240	24	1,372	Vertisol	common bean	Bitew et al. (2021)
10° 42′ N, 37° 16′ E	ET_finoteselam	Ethiopia	Ethiopian montane grasslands and woodlands	1,917	21	1,272	Rhodic Nitisol	common bean	Bitew et al. (2021)
4°34′ N, 38° 12′ E	ET_yavello	Ethiopia	Northern Congolian forest-savanna mosaic	1,850	21	650	red-brown clay loam	cowpea	Alemseged et al. (1996a, 1996b)
9°26′ N, 42° 03′ E	ET_alemaya	Ethiopia	Ethiopian montane grasslands and woodlands	1,980	17	790	Fluvisol	common bean	Tamado et al. (2007)
9°15′ N, 41° 06′ E	ET_hirna	Ethiopia	Ethiopian montane grasslands and woodlands	1,870	24	1,045	Vertisol	common bean	Tamado et al. (2007)
04°14′ S, 35° 35′ E	TZ_babati	Tanzania	Central Zambezian Miombo woodlands	1,650	19.3	840–1,170	Ferrasol	pigeonpea	Myaka et al. (2006), Adu-Gyamfi et al. (1997)
06°13′ S, 36° 53′ E	TZ_gairo	Tanzania	Eastern Miombo woodlands	1,310	19.5	450–940	Ferralic Cambisol	pigeonpea	Myaka et al. (2006), Adu-Gyamfi et al. (1997)
14°39′ S, 35° 35′ E	MW_nyambi	Malawi	Eastern Miombo woodlands	770	22	690–990	Cambisol	pigeonpea	Myaka et al. (2006), Adu-Gyamfi et al. (1997)
15°53′ S, 34° 57′ E	MW_ntonda	Malawi	South Malawi montane forest-grassland mosaic	820	23	950–1,120	Ferrasol	pigeonpea	Myaka et al. (2006), Adu-Gyamfi et al. (1997)
7°38′ S, 36° 01′ E	TZ_ikuwala	Tanzania	Eastern Miombo woodlands	1,370	19	500	Kandic Paleustalf	cowpea	Vesterager et al. (2007), Vesterager et al. (2008)
20°10′ S, 28° 35′ E	ZW_nqindi	Zimbabwe	Southern Africa bushveld	1,320	18	190–354	Luvic Arenosol	cowpea	Masvaya et al. (2017)

Note. Ecozones are following the terminology from Olson and Dinerstein (2002).

Table 2
Experimental Setup Information Used for Site Initialization Extracted From the Experimental Literature (Table 1)

Site	N fertilizer rate sole maize (kg N ha^{-1})	N fertilizer rate legume (kg N ha^{-1})	N fertilizer rate intercropping (kg N ha^{-1})	N fertilizer type	Planting density sole maize (10^3 plants ha^{-1})	Planting density intercropped maize (10^3 plants ha^{-1})	Planting density sole legume (10^3 plants ha^{-1})	Planting density intercropped legume (10^3 plants ha^{-1})
GH_kpataribogu	50	0	25	Urea	53.3	26.6	10.6	53.3
GH_bundunia	50	0	25	Urea	53.3	26.6	10.6	53.3
GH_nyankpala	0	0	0	Urea*	55.6	55.6	13.3	55.6
NG_zaria	120	40	120	Urea	53.3	53.3, 41.0	53.3	53.3
NG_iburu	120	40	120	Urea	53.3	53.3, 41.0	53.3	53.3
ET_alemaya	50	0	50	Urea	44.4	44.4	250.0	125.0
ET_hirna	50	0	50	Urea	44.4	44.4	250.0	125.0
ET_adet	180	32	180	Urea	40.0	40.0	250.0	133.3
ET_finoteselam	180	32	180	Urea	40.0	40.0	250.0	133.3
ET_mecha	128	41	128	Urea*	44.4	44.4	250.0	125.0
ET_south_achefer	128	41	128	Urea*	44.4	44.4	250.0	125.0
ET_yavello	0	0	0	Urea*	55.0, 30.0, 20.0	55.0, 30.0, 20.0	50.0	50.0
TZ_ikuwala	15	15	15	NH_4SO_4	37.5	18.8	75.0	37.5
TZ_babati	0	0	0	Urea*	53.3*	53.3*	53.3*	53.3*
TZ_gairo	0	0	0	Urea*	53.3*	53.3*	53.3*	53.3*
MW_nyambi	0	0	0	Urea*	53.3*	53.3*	53.3*	53.3*
MW_ntonda	0	0	0	Urea*	53.3*	53.3*	53.3*	53.3*
ZW_nqindi	0, 40	0	0, 40	NH_4NO_3	37.5	37.5	74.0	74.0

Note. *If not stated in the experimental reference paper, urea was used as fertilizer type and plausible plant densities of maize and pigeon pea were assumed. The choice was based on the planting densities recommended for Malawi (FAO) (https://openknowledge.fao.org/server/api/core/bitstreams/fde99366-c5ae-4a07--b701-5e9b5b691575/content), which correspond to current recommendations in Tanzania, see https://www.iprjb.org/journals/index.php/IJA/article/view/2314. These entries are marked with an asterisk.

located in the Lake Turkana-Sudd Grasslands, Bushlands & Forests Bioregion (AT21) in Ethiopia characterized by average temperatures of 17–24°C and 790–1,400 mm annual precipitation and fertile soils, mainly Nitisoils, but also Fluvisols and Vertisols (Alemayehu et al., 2017; Alemseged et al., 1996a, 1996b; Bitew et al., 2021; Tamado et al., 2007). Another six sites were located in the Greater African Subequatorial Savannas & Mixed Woodlands Bioregion (AT11) in Tanzania, Malawi and Zimbabwe and showed annual average temperatures between 18 and 32°C and annual precipitation between 650 and 900 mm. Soil types in this bioregion were Ferrasols and Cambisols for the sites in Malawi and Tanzania, and Arenosols in Zimbabwe (Table 1) Adu-Gyamfi et al., 2007; Masvaya et al., 2017; Myaka et al., 2006; Vesterager et al., 2007, 2008).

Mineral fertilizer rates mostly applied in the form of urea ranged between 0 and 180 kg N ha^{-1} yr^{-1}, with the lowest rates applied at sites in Malawi and Tanzania, and highest rates in Ethiopia (Table 2). Sole legume systems were usually not fertilized, with soybean being the only exception, fertilized up to 40 kg N ha^{-1} yr^{-1}. While most experiments used the same amounts of fertilizer for the intercropping system as applied for sole maize cropping, two experiments only applied half of the sole maize N rate in the intercropping system (Table 2). Organic fertilizers were not applied in any of the experiments. Planting densities for maize varied between 37,500 and 55,556 plants ha^{-1} in the experimental studies, and was either kept constant (additive design) or reduced up to 50% (substitutive design) in intercropping systems (Table 2).

2.3. Model Description LandscapeDNDC

The LandscapeDNDC model framework consists of different sub-models that provide the capability to simulate C, N and water cycling in the plant soil system of arable, grassland and forest ecosystems (Haas et al., 2013; Kraus et al., 2016). All sub-models represent the respective ecosystem domains in a vertical 1-D column, thereby assuming laterally homogeneous conditions. In this study, we used the *PlaMo^x* model (Kraus et al., 2016;

Liebermann et al., 2020) for simulating the crop growth in hourly timesteps together with the sub-models *MeTr*^{x} for C and N soil biogeochemistry (Kraus et al., 2015), ECM for microclimate (Grote et al., 2009), and the original DNDC routines for the water cycle (Kiese et al., 2011; C. Li et al., 1992). For this study, version 1.35.2 (revision 11165) was used (https://ldndc.imk-ifu.kit.edu/). LandscapeDNDC has been evaluated in various studies for predicting yields, soil C and N dynamics and associated greenhouse gas emissions and nitrate leaching (Denk et al., 2019; T. Houska et al., 2017; Kraus et al., 2016; Liebermann et al., 2018, 2020; Rahimi et al., 2021). In SSA, recently (Rahimi et al., 2021) parameterized and used LandscapeDNDC for simulating biomass at cropland, grassland and savanna sites in Sahelian and Sudanian Savanna systems.

2.4. *PlaMo*^{x} Vegetation Model With Its Particularities for Intercropping Systems

The PlaMo^x vegetation model simulates plant growth for crops and grass species based on the photosynthesis model of Farquhar et al. (1980) and Ball et al. (1987). Process descriptions are formulated to be generally valid, and species are distinguished by specific parametrizations. PlaMo^x defines the plant compartments leaf, stem, roots, and fruit/storage. Leaves and stems are particularly responsible for growth and structure. For grass species, the fruit/storage compartment represents compounds that can be reallocated, for example, after defoliation. For crop species, the fruit/storage compartment represents the grain yield and is a final carbon and nitrogen sink without reallocation option. Petersen et al. (2021) gives a more detailed description of PlaMo^x including plant phenology, C and N allocation, photosynthesis and N uptake. Here we focus on the description of intercropping, that is, the competition for light, water and N, as well as on biological N_2 fixation (BNF) by legumes and its effects on two simultaneously grown plants. PlaMo^x simulates a user-defined number of individual crop types (usually one or two, i.e., main and undersown crop) that are laterally homogeneously distributed. Vertically, PlaMo^x considers plant height and rooting depth and associated with this, species-specific vertical distributions of leaf biomass/area index as well as fine root biomass. In terms of competition for light, the vertical distribution of LAI determines the amount of radiation absorbed by a species, which means that smaller species are shaded by taller ones. The absorption of light within the canopy is based on species-specific extinction coefficients (Spitters et al., 1986).

Belowground, the vertical distribution of fine root biomass regulates the potential plant water and nutrient uptake. The concept of lateral homogeneity implies that water and nutrients are equally available across a simulation unit, for example, a field or a plot. Thus, spatially explicit fertilizer application (spot application) to single species cannot be represented by the model. Species-specific nitrogen uptake is given by

$$\frac{dN_{x,up}}{dt} = \int_0^Z m_{root}(z) \cdot \Omega_{N_x,use} \cdot f_T(z) \cdot \frac{N_x(z)}{\Omega_{N,up} + N_x(z)} \tag{1}$$

Species-specific nitrogen uptake depends on soil depth z, specific fine root biomass m_{root}, nitrogen concentration N_x (i.e., NH_4 or NO_3), temperature response function f_T and species-specific parametrization for nitrogen uptake rate $\Omega_{N_x,use}$ (kg N per kg DM) and nitrogen affinity $\Omega_{N,up}$ (kg N m^{-3}).

Actual N_2 fixation by legumes $\frac{dN_{fix}}{dt}$ is determined by total plant N demand under optimum growth conditions N_{opt} multiplied by the unitless fraction Ω_{fix} that might be fixed under conditions of maximum BNF and regulated by plant development $\frac{d\,DVS}{dt}$:

$$\frac{dN_{fix}}{dt} = \frac{d\,DVS}{dt} \cdot \Omega_{fix} \cdot N_{opt} \tag{2}$$

Biological N_2 fixation by legumes comes along with carbon costs, with a default carbon cost parameter (C_{eff}) of 5 g C per g N:

$$\frac{dC_{fix,resp}}{dt} = \frac{dN_{fix}}{dt} \cdot C_{eff} \tag{3}$$

The fixed N, particularly if allocated to root biomass, may become available to other plants after senescence and mineralization (or after harvest for stover remaining on the field) and can in this way affect subsequent N availability of the other species.

Soil N availability in the form of NH_4 and NO_3 and dissolved organic N for plant growth is calculated in the soil biogeochemical sub-model *MeTr*^{x} and depends on mineralization rates and competition of plants with microbial N assimilation. Legume N demand is fulfilled first by soil available N, and only if the N demand is higher than the actual soil N availability, the remaining is (fully or partly) acquired via biological N_2 fixation. Thus, biological N_2 fixation is downregulated by the rate of fertilizer increasing soil N availability.

2.5. Model Setup and Initialization

The model requires input data on initial soil properties, and uses daily climate drivers and atmospheric boundary conditions as well as agricultural management. Vegetation growth is prescribed by species parameters and initial plant biomass. The soil parameters for initialization are soil profile information on bulk density, pH, soil texture (i.e., clay, silt, and sand content), organic C and N content, and soil hydrological parameters (i.e., field capacity, wilting point, saturated hydraulic conductivity). Soil properties were established to a depth of 1 m in layers of 1 cm up to a depth of 40 cm, layers of 5 cm up to a depth of 80 cm and layers of 10 cm below 80 cm. All soil information was first acquired from ISRIC-WISE (0.08°spatial resolution; International Soil Reference and Information Center-World Inventory of Soil Emission Potentials) soil dataset (Batjes, 2012) and if available replaced by site-specific soil properties (at 10 sites) mostly for the upper 0–20 or 0–40 cm soil depths.

Input climate data were maximum and minimum temperature (°C), precipitation (mm), relative humidity (%), global radiation (W m^{-2}), and wind speed (m s^{-1}). These data were extracted for the period 1997–2020 at the grid cell containing the site from the ERA5 climate data set (ERA5; 0.1° × 0.1° resolution; Muñoz Sabater, 2019). For the air chemistry module, dry and wet deposition of oxidized and reduced N compounds (NHx and Noy) were taken from the ISIMIP3a N deposition data set assuming equal deposition each day (monthly; 0.5° × 0.5° resolution, simulated by NCAR Chemistry-Climate Model Initiative (CCMI; Tian et al., 2018). The atmospheric CO_2 concentration was set to 400 ppm.

Agricultural management practices such as sowing, fertilization (i.e., type and application rate) and harvesting events were established according to the management descriptions at each study site in the respective reference study. In few cases, where the sowing or harvest dates were not explicitly stated, they were inferred from information about the climate conditions of the season and the given maturity period for the crop, that is, harvest dates were calculated as the date when the cumulative growing degrees reach maturity plus 2 weeks, and sowing dates by the same rule applied backward in time. Unless otherwise stated in the experiment, we assumed standard tillage to a depth of 0.2 m depth the day before planting and a crop residue return of 30% for both maize and legume stover left on the field. According to the model's best practice, three spin-up years were simulated in order to reach soil pools close to the equilibrium state given the target soil C and N contents.

Competition between intercrops is influenced by the planting densities of each component crop, with farmers optimizing plant densities for the main crop to maintain its productivity. Since *PlaMo*^{x} does not account for seed failure, the initial biomass is given by the average seed weights multiplied with the final plant density (plants ha^{-1}) for each treatment at each site (Table 2). Seed weights were taken from the WOFOST model (v.6.1) and were 0.3 g per plant for maize (or hundred-seed-weight of 30 g), 0.13 g per plant for cowpea, 0.4 g per plant for soybean, 0.125 g per plant for peanut, 0.386 g per plant for bean, and 0.08 g per plant for pigeon pea (http://github.com/ajwdewit/WOFOST_crop_parameters).

2.6. Species Parameterization and Calibration

In order to determine suitable species parameters, we performed a multi-site parameter calibration on half of our study sites. The term *multi-site calibration* refers to using multiple sites within a bioregion at once in the calibration process. In that way, parametrizations are optimized for each crop in each bioregion in contrast to single-site calibration. Default species parameters for maize parameterized in West Africa (West Sudanian Savanna Bioregion, Rahimi et al., 2021) were not suitable for the intercropping situation, since maize plants were shaded by the legume intercrops and outcompeted, so the calibration needed to ensure parameters (for growth stages, photosynthesis and leaf area) of both maize and intercrops allow for simultaneous development of both crops.

Table 3
Performance Measures Per Crop and Variable for the Average of the Best Runs in the Calibration (Left) and Validation (Right) Across Sole and Intercrops

		Calibration							Validation						
		RMSE	Bias	rRMSE	Rbias	r	n	p	RMSE	Bias	rRMSE	Rbias	r	n	p
Aboveground biomass (kg DM ha^{-1})	Maize	2493	−153	0.45	−0.03	0.68	64	<0.01	3,681	−225	0.66	−0.04	0.4	36	<0.01
	Bean	313	−44	0.09	−0.01	NA	2	–	1,201	684	0.25	0.14	NA	2	–
	Cowpea	700	100	0.43	0.06	0.51	22	<0.01	1,431	−985	0.60	−0.41	0.06	8	0.72
	Peanut	415	−40	0.41	−0.04	0.72	8	<0.01	335	54	0.43	0.07	0.75	8	<0.01
	Pigeon pea	1,671	−1,113	0.37	−0.24	0.63	4	<0.01	983	−378	0.44	−0.17	−0.7	4	<0.01
	Soybean	1,682	−693	0.33	−0.14	0.56	14	<0.01	2025	1,223	0.57	0.35	0.43	14	<0.01
Grain yields (kg DM ha^{-1})	Maize	1,341	−431	0.55	−0.18	0.49	72	<0.01	1,229	−5	0.50	0	0.67	44	<0.01
	Bean	460	−73	0.51	−0.08	0.28	14	0.02	540	189	0.63	0.22	0.29	14	<0.01
	Cowpea	630	−259	0.72	−0.29	−0.28	30	<0.01	659	−387	0.65	−0.38	0.06	8	0.73
	Peanut	118	3	0.5	0.01	0.75	8	<0.01	111	−34	0.48	−0.14	0.29	8	0.07
	Pigeon pea	137	21	0.3	0.05	−0.61	4	<0.01	154	−29	0.55	−0.1	−0.82	4	<0.01
	Soybean	614	−285	0.4	−0.18	0.42	14	<0.01	618	143	0.50	0.11	0.36	14	<0.01
Leaf area index (−)	Maize	1.2	−0.6	0.42	−0.21	0.39	16	<0.01	1.6	−1.2	0.58	−0.44	0.5	14	<0.01
	Bean	1.0	−0.9	0.6	−0.55	0.13	4	0.58	0.9	−0.8	0.42	−0.39	0.26	4	0.27
	Cowpea	0.8	−0.6	0.31	−0.23	−0.16	6	0.39	2.1	−2.1	0.70	−0.7	–	4	–
	Peanut	3.1	−3.1	0.88	−0.87	NA	4	–	3.1	−3.1	0.87	−0.87	–	4	–
	Soybean	1.7	−1.4	0.36	−0.29	0.56	10	<0.01	1.6	−0.4	0.40	−0.1	0.44	10	<0.01
Nitrogen in aboveground biomass (kg N ha^{-1})	Maize	19.8	−9.6	0.44	−0.22	0.52	32	<0.01	16.5	7.9	0.69	0.33	−0.18	24	0.06
	Cowpea	27.9	−17.4	0.58	−0.36	0.37	16	<0.01	21.5	−10.1	0.61	−0.29	0.06	8	0.72
	Peanut	8.4	−2.6	0.36	−0.11	0.58	8	<0.01	6.6	−4.0	0.30	−0.18	0.76	8	<0.01
	Pigeon pea	18.5	−11.0	0.31	−0.18	0.46	4	0.04	19.8	−1.5	0.58	−0.04	−0.72	4	<0.01
	Soybean	35.0	−23.9	0.32	−0.22	0.54	8	<0.01	53.9	23.4	0.66	0.29	0.28	8	0.08
Nitrogen fixed in aboveground biomass (kg N ha^{-1})	Cowpea	14.0	8.9	0.67	0.42	0.33	12	<0.01	11.6	3.0	0.47	0.12	0.03	8	0.85
	Peanut	6.2	1.2	0.48	0.09	0.54	8	<0.01	7.6	−5.9	0.39	−0.3	0.76	8	<0.01
	Soybean	22.3	5.8	0.29	0.08	0.46	8	<0.01	57.5	50.5	1.06	0.93	0.34	8	0.03

Note. RMSE and bias are in the standard units of the respective value as indicated in the first column. Relative RMSE (rRMSE) and relative bias (rbias) have no units (−). Further, the correlation coefficient *r*, the sample size *n* and the *p*-value of the correlation is given.

With the goal to optimize one bioregion-specific parameter set per species that represents the crop growth in sole and with the identical parameter set in intercropping systems, we calibrated the species parameters with an automatic calibration procedure as described in the next paragraph. The species parameter ranges displayed in Table S1 in Supporting Information S1 were selected for calibration, since they dominantly affect growth dynamics and indirectly affect species interaction. Thresholds for parameter ranges were set to span physiologically meaningful values according to each species' properties. All other species parameters were kept as calibrated parameterized and extensively tested by Rahimi et al. (2021) for sole cropping systems.

For the automatic calibration a multi-criteria analysis was performed in order to find the optimum sets of species parameters (see Table S1 in Supporting Information S1). We used uniform parameter distributions in a Latin Hypercube sampling with 10,000 repetitions, using the spotpy package in Python, with a routine to automatically perform the LandscapeDNDC model runs at the calibration sites (Houska et al., 2015). The simulation result of each run was compared with the respective observational data using the relative root mean squared error (rRMSE) as the goodness of fit criteria. Target variables were aboveground plant biomass, grain yields, total N plant uptake, maximum LAI as well as N_2 fixed and located in aboveground legume biomass. The number of observations per variable is listed in Table 3. The optimum set of parameters was defined as the set which minimizes the relative

RMSE across all variables, sites and crops (i.e., the objective criterion is the average of all variables, site and crop rRMSEs). Thus, the objective function of the multi-criteria analysis can be described as

$$rRMSE = \frac{1}{m}\sum_{j=1}^{m}\frac{1}{n}\sum_{i=1}^{n}\frac{\sqrt{\frac{1}{x}\sum_{k=1}^{x}\left(y_{sim,i,j,k} - y_{obs,i,j,k}\right)^2}}{\frac{1}{x}\sum_{k=1}^{x} y_{obs,i,j,k}} \tag{4}$$

Where i are the variable yields, aboveground biomass, N in aboveground biomass, N_2 fixed, and j are the sites. We build the relative RMSE across the x observations of variable i at site j and average these rRMSEs across the n variables and m sites. We used as our simulation result the average output (not average parameters!) across the best 0.1% model runs, corresponding to the simulations with the 10 best sets of parameters. The variation across these 10 runs can be used as an estimate for uncertainty when upscaling to regional levels.

The python package spotpy (Tobias Houska et al., 2015) was used as a framework for automatic parameter sampling and model re-initialization. Species parameters were calibrated per crop across sites for a given bioregion to obtain generally consistent (site-independent) parameter sets, to avoid excess degrees of freedom, and to achieve robustness for potential spatial upscaling approaches. In order to account for the effects of different growing season lengths and temperatures at different sites, the parameter cumulative growing degrees (°C; Petersen et al., 2021) required for maturity (gdd_maturity) was specifically set per site, in the manner that we calculated it from the experimental sowing and harvest dates and the respective climate data.

2.7. Land Equivalent Ratio (LER)

For comparing yields for sole and intercropping systems, we calculated the land equivalent ratio (LER). According to FAO, the LER is the ratio of the area under sole cropping to the area under intercropping needed to give equal amounts of yield at the same management level (FAO, 1985; https://www.fao.org/3/x5648e/x5648e0m.htm). Partial LERs give the ratio for each component crop, and the sum of all partial LER results in the total LER. It is calculated from yields as follows:

$$\text{LER} = \sum_{j=1}^{n}\frac{x_{inter,j}}{x_{sole,j}} \tag{5}$$

Here, $X_{inter,\,j}$ are intercropping yields of the jth crop species, x_{sole} are sole cropping yields of the jth crop species of the n different crops. The LER is widely used as a measure of productivity in intercropping systems, because it summarizes the yield benefit of intercropping as one number.

2.8. Long Term Simulations of Intercropping and Residue Management

To assess long term (20 years) effects of intercropping in combination with different residue management and N fertilizer application strategies, we conducted scenario simulations at all sites using the calibrated species parameters. We set up simulations for the period 1997 to 2020, from which the period 2000–2020 was analyzed, and for site simulations, the first three years 1997–1999 were dropped as spin-up periods. During the spin-up period, we consistently simulated sole maize with 30% of aboveground residues left on the fields and its site-specific "default" fertilizer application. The management dates and setup for the long-term scenario simulations were chosen to be identical to those used in the calibration and validation runs and repeated annually (sowing and harvest dates, planting densities, fertilizer application dates). For sole maize and intercropped maize-legume systems, we ran four scenarios differing in the fraction of stover left on field (0%, 30%, 70% and 100%) as the residue management strategies. In intercropping systems, both legume and maize stover fractions left on fields were set simultaneously, that is, 100% of stover left on field means 100% of both maize and legume stover. In all scenarios, legume and maize grains were exported and all belowground residues were kept in the soil. To maintain realistic management practices, wooden plant components of pigeon pea that is, about 65% of aboveground plant biomass were always exported, and only the remaining plant biomass was considered within different residue scenarios. Fertilizer scenarios considered fertilizer application rates of 0, 50, 100 and 150 kg N ha^{-1} yr^{-1} (0–150N). Simulations were executed in a full factorial design with varying fertilizer and residue management combinations for any of the intercropping systems. Original N fertilizer types and rates which differed across the sites were kept unchanged for the spin-up period to acquire realistic site-specific soil conditions before starting the scenarios. For the long-term simulations, 10 runs using the 10 best sets of parameters (i.e., each of the 10 simulations used a different set of parameters selected from the 0.1% of calibration runs with the lowest RMSE in Section 2.6) were performed for each sole crop and crop combination in each scenario and the mean across the 10 runs was reported together with its standard error (sem).

2.9. Statistical Analysis

To quantify the performance in the model validation exercise, we used the RMSE, bias, and Pearson's r (and r^2) as measures for goodness-of-fit of our simulation results. The relative RMSE (rRMSE) and relative bias (rBIAS) were calculated by dividing the RMSE or bias, respectively, by the mean of observations.

In order to analyze long-term simulation results, we used linear regression models to quantify the effects of intercropping, residue management and fertilizer rate on grain yields, N yields, and soil C and N stocks. We used fixed effects for intercropping and residue management, and a linear term for assessing the effect of fertilizer rate on the respective target variables. Since nonlinear terms for fertilizer rate did not improve the model (did not lower the AIC) we used the linear regression. The standard level of significance 5% was applied. Linear regression models were also used to determine trends in grain yields, N in grain yields, soil C and soil N over the 20 years simulations. Residual analysis showed that the residuals of all statistical models were in line with the assumptions of a Gaussian distributed homoscedastic error term with a mean of zero. Data analyses were performed in R version 4.2.3 (R Core Team, 2023).

3. Results

3.1. Calibration and Validation

Overall, LandscapeDNDC could reproduce aboveground biomass and other biomass related parameters (Figures 2a–2c) in good agreement with field measurements with r values ranging between 0.90 and 0.98 and relative RMSE between 21% and 31% at the independent validation sites. The model performed well in predicting aboveground biomass N, although it showed slightly lower accuracy in estimating the LAI with a relative RMSE of 55% at the validation sites.

Aboveground biomass simulations agreed well with the observations, with a small underestimation in the calibration of 8% and relative RMSE of 14% ($r = 0.98$; Figure 2a). Similarly, aboveground biomass simulations at the validation sites showed a minor underestimation by 1% and relative RMSE of 26% across all crops ($r = 0.9$; Figure 2a). These similar performances at calibration and validation sites indicate that parameters were not overfitted, which was also confirmed with the other target variables: Average grain yields across the calibration sites were well represented by the model, showing a minor underestimation of 18% and a relative RMSE of 25% ($r = 0.99$; Figure 2b). Simulating grain yields at the independent validation sites across SSA with the calibrated species parameters confirmed these results showing a slight underestimation by 7% and a relative RMSE of 21% ($r = 0.95$; Figure 2b). Similarly, nitrogen in aboveground biomass simulations showed an underestimation by 25% at the calibration sites, consistent across crops, and relative RMSE of 34% ($r = 0.95$; Figure 2c). At the independent validation sites, precision and accuracy were higher with a slight overestimation by 7% and relative RMSE of 31% ($r = 0.97$; Figure 2c), indicating a robust parametrization regarding N uptake. Simulated LAI at the calibration sites was 39% lower than observed (Figure 2d), and at the validation sites underestimated by 40% with a relative RMSE of 55% (Figure 2d), which was less accurate compared to the other variables. Nitrogen fixed from the atmosphere and allocated to aboveground biomass was overestimated by 12% at the calibration sites (rRMSE 22%; $r = 0.97$; Figure 2e). At the validation sites, there was a larger positive bias (48%) primarily due to an overestimation in soybean N_2 fixation, while the other crops were simulated more accurately ($r = 0.98$; Figure 2e). Further details on the evaluation per crop are given in Table 3. In summary, the independent validation demonstrated that the model was capable of accurately simulating the mean observed characteristics of the major crops.

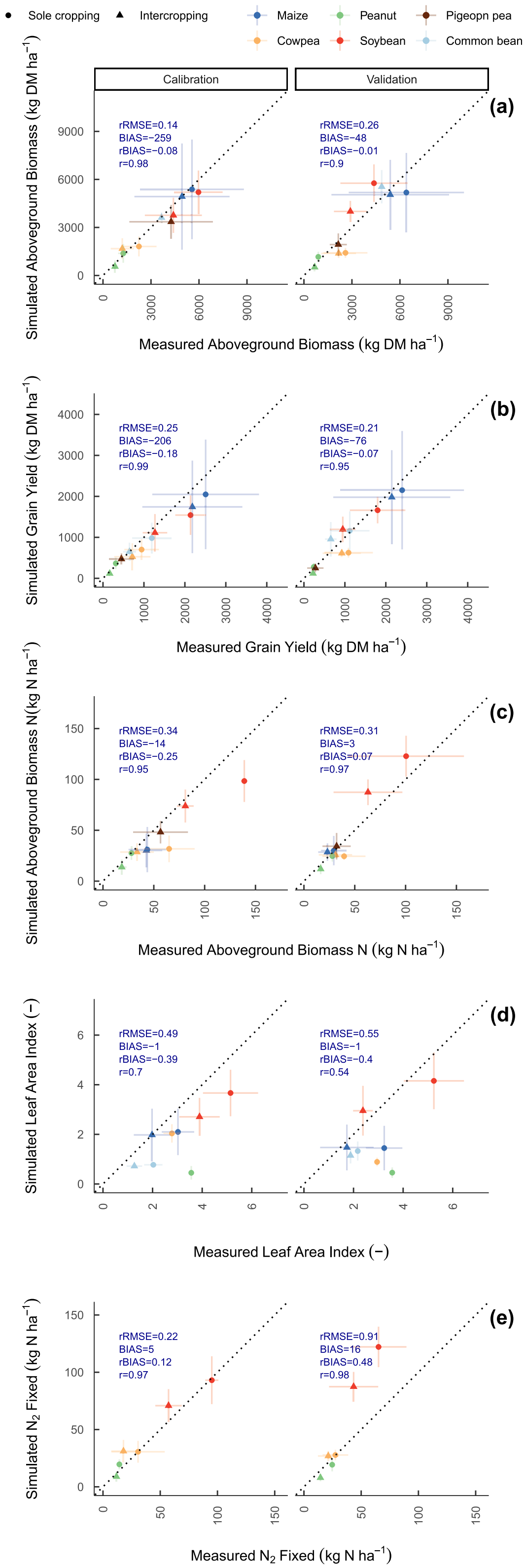

Figure 2. Scatter plots of measured (x-axis) versus simulated (y-axis) aboveground biomass (a), grain yield (b), aboveground biomass N (c), leave area index (d) and N_2 fixed allocated to aboveground biomass (e) for all crops for calibration (left) and validation data sets (right). The horizontal bars represent the variability (sd) across sites and the vertical bars represent the variability (sd) of the site-mean following the model runs of the 10 best parameter sets.

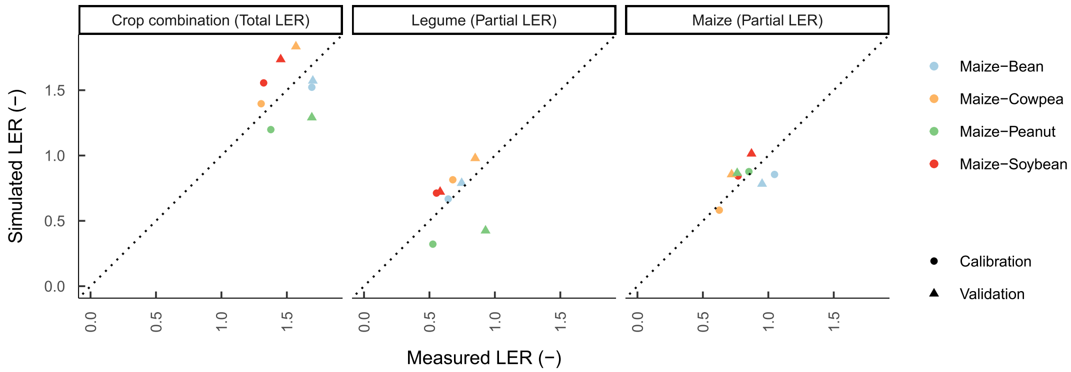

Figure 3. Measured simulated total (maize + legume) LER (right) and partial LER of legumes (middle) and maize (right) for different intercropping systems (crop combinations) at calibration and validation sites.

3.2. Land Equivalent Ratios (LER) and Overall Intercropping Effect on Productivity

Land equivalent ratios were simulated with reasonable accuracy for the different cropping systems (Figure 3). While the partial LER of cowpea was overestimated, the partial LER of maize in the maize-cowpea system was accurately simulated. Soybean partial LER showed a similar moderate overestimation, while the partial LER of maize in the maize-soybean system was slightly overestimated. In contrast, the partial LER of groundnut was widely underestimated due to an underestimation in intercropping yields. Bean simulations show a very similar partial LER compared to the observations (Figure 3). Intercropping came along with a maize yield penalty indicated by partial LERs of maize below 1. Experimental sites showed an average maize yield penalty of 12% (301 kg DM ha^{-1} yr^{-1}), which was well represented in our simulations (12%, 248 kg DM ha^{-1} yr^{-1}) (Table S2 in Supporting Information S1). The maize yield penalty was highest for maize-cowpea systems, and lowest for maize-bean and maize-soybean systems (Figure 3).

3.3. Long-Term Scenario Simulations

3.3.1. Effects of Intercropping, Residue Management and Fertilizer Application Rates on Yields

Simulated yields were primarily affected by fertilizer application rates (17.3 kg DM ha^{-1} yr^{-1} per kg N fertilizer, $p < 0.05$). Yields significantly increased in intercropping systems compared with sole maize systems (271 kg DM ha^{-1} yr^{-1}, $p < 0.05$; average of 20 years across scenarios) (Figure 4a, Table 4). The intercropping effect depended on the fertilizer application rate, with the largest intercropping effect observed in the 0N scenario (649 kg DM ha^{-1} yr^{-1}, $p < 0.05$), and a significantly lower intercropping effect in the 50N scenario (182 kg DM ha^{-1} yr^{-1}, $p < 0.05$). For fertilizer rates of 100 kg N or more, the scenario simulations showed no significant intercropping effect on yields. In the 0N scenarios, returning 100% of crop residues increased yields by 133 kg DM ha^{-1} yr^{-1} compared with removing all aboveground residues ($p < 0.05$), while residue return showed no significant effect on yield in the 50–150N scenarios.

Sole maize yields in the 0N fertilizer scenarios decreased significantly over the 20 year in all residue scenarios with a trend of −12.2 to −28.2 kg DM ha^{-1} yr^{-1} ($p < 0.05$). In contrast, the intercropping system showed yield decreases over the 20 years only at the 0N fertilizer scenario with no residues left on the field (−9.3 kg DM ha^{-1} yr^{-1}, $p < 0.05$), while residue amendments led to yield stability even at 0N. No significant yield trends occurred at medium to high fertilizer rates (50–150 kg N) for sole and intercropping systems evaluated across legume types.

The total N grain yields and thus crude protein harvest was significantly higher in intercropping systems (mean effect 26.8 kg N ha^{-1} yr^{-1}, $p < 0.05$) compared to sole maize systems (Figure 4b) due to the contribution of legumes with their higher N contents compared to cereals, and due to higher N concentrations of maize grain in intercropped compared to sole cropped systems. The absolute amount of N in grain yields increased with fertilizer application rates (0.24 kg N ha^{-1} yr^{-1} per kg N fertilizer, $p < 0.05$) as well as with the fraction of residues left on the field (3.2 kg N ha^{-1} yr^{-1} higher for 100% compared to 0% residues, $p < 0.05$) (Figure 4b). The intercropping effect on N grain yields was largest at the 0N treatment (35.0 kg N ha^{-1} yr^{-1}, $p < 0.05$) and decreased slightly with

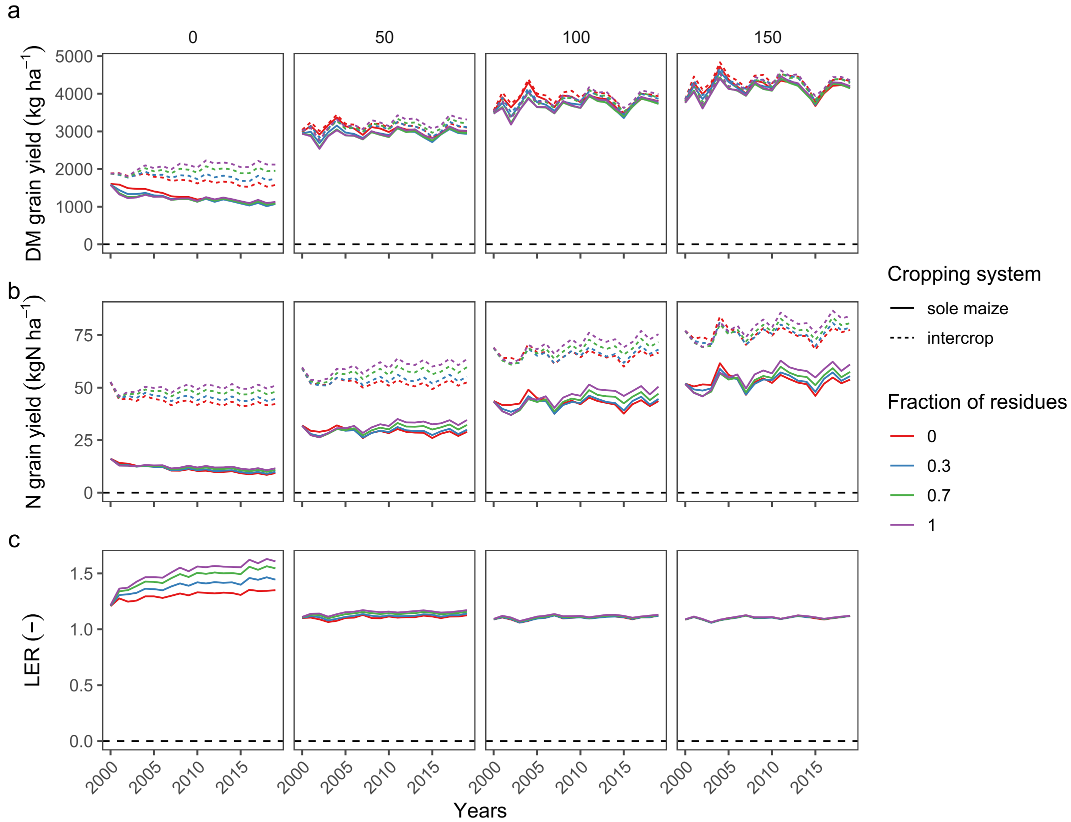

Figure 4. Trends in (a) DM and (b) N yields for sole (solid line) and intercropped maize systems (total of maize + legume dashed line) as well as (c) LER shown at four different fertilizer levels (panels left to right) and at four different residue management practices (color-coded fraction of 0%–100% of residues left on field). Annual data of the 20 years' scenario runs (2000–2020) averaged across sites and legume types.

increasing fertilizer levels (50N 25.7 kg ha^{-1} yr^{-1}; 150N 22.9 kg ha^{-1} yr^{-1}). However, unlike dry matter grain yields, the intercropping effect on N grain yields persisted at higher fertilizer application levels due to the contribution of N-rich legume grain yields providing higher absolute crude protein amounts compared to maize yields. The average amount of N_2 fixed via legumes in the unfertilized intercropping systems was 61 kg N ha^{-1} yr^{-1}, ranging from 12 kg N ha^{-1} yr^{-1} in maize-peanut systems to 134 kg N ha^{-1} yr^{-1} in maize-soybean systems. The 150N fertilizer rate reduced the amount of N_2 fixed via legumes to an average of 38 kg N ha^{-1} yr^{-1}, with the lowest N_2 fixation rate for pigeon pea of 4 kg N ha^{-1} yr^{-1} and the highest N_2 fixation rate for soybean of 104 kg N ha^{-1} yr^{-1}.

Harvested N grain yields decreased significantly over the 20 years in the sole maize systems at 0N at all residue scenarios (−0.27 to −0.75 kg N ha^{-1} yr^{-1}, $p < 0.05$), as well as at 50N if all residues were removed (−0.17 kg N ha^{-1} yr^{-1}, $p < 0.05$; Figure 4b). In contrast, N grain yields did not decrease in the intercropping systems, even not at 0N without residue return, when dry matter grain yields decreased. This resulted from stable N concentration of the maize grain in intercropping systems compared to decreasing grain N concentration for sole maize. Symbiotic N_2 fixation rates showed no significant trend over 20 years.

Following the pattern in yields, LER was highest in the 0N fertilizer scenario (1.41), and lower at increased fertilizer application rates (1.10–1.13, $p < 0.05$). At 0N application, LER increased with increasing rate of residues left in the field, while there was no benefit of residue return on LER when fertilizer was applied ($p < 0.05$; Figure 4c). The differences in yield development between sole and intercropping systems (i.e., sole maize yield decrease) resulted in a positive trend for the LER at the systems without N fertilizer, underscoring the long-term benefits of intercropping compared to sole maize cropping systems at 0N. Particularly, if residues remain on the fields, growing sole maize and sole legume systems would need 11%–51% more area (LER of 1.11–1.51) to

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Table 4

DM and N Exports With Harvest (kg ha^{-1} yr^{-1}) for Sole Maize and Intercropping Systems (Joint Maize + Legume Exports) as Well as Annual Change in Soil C Stocks (kg C ha^{-1} yr^{-1}) and Soil N Stocks (kg N ha^{-1} yr^{-1}) (Averaged Across Sites and Intercrop Legume Species)

Residue fraction (−)	0N		50N		100N		150N	
	Sole maize	Intercrops	Sole maize	Intercrops	Sole maize	Intercrops	Sole maize	Intercrops
DM grain harvest (kg DM ha^{-1} yr^{-1})								
0	1,276 (12)	1,702 (11)	3,038 (27)	3,136 (22)	3,816 (42)	3,924 (36)	4,182 (50)	4,327 (44)
0.3	1,216 (11)	1,798 (11)	2,940 (23)	3,089 (20)	3,716 (38)	3,816 (32)	4,162 (47)	4,271 (41)
0.7	1,207 (10)	1,947 (12)	2,913 (22)	3,131 (21)	3,660 (35)	3,798 (31)	4,098 (44)	4,220 (39)
1	1,222 (9)	2,064 (13)	2,936 (22)	3,200 (22)	3,684 (35)	3,849 (31)	4,122 (44)	4,262 (39)
N in grain harvest (kg N ha^{-1} yr^{-1})								
0	11 (0.1)	43 (0.6)	29 (0.1)	52 (0.5)	43 (0.3)	65 (0.4)	53 (0.5)	76 (0.5)
0.3	11 (0.1)	45 (0.6)	29 (0.1)	54 (0.5)	43 (0.3)	66 (0.5)	53 (0.4)	76 (0.5)
0.7	12 (0.1)	48 (0.6)	30 (0.1)	57 (0.5)	44 (0.3)	68 (0.5)	54 (0.4)	77 (0.5)
1	12 (0.1)	50 (0.6)	32 (0.1)	60 (0.5)	46 (0.3)	70 (0.5)	56 (0.4)	79 (0.5)
Change in soil C stocks (kg C ha^{-1} yr^{-1})								
0	−317 (5)	−307 (5)	−247 (8)	−246 (6)	−231 (8)	−226 (6)	−222 (9)	−214 (7)
0.3	−280 (5)	−221 (5)	−135 (8)	−116 (7)	−92 (9)	−74 (7)	−66 (10)	−47 (8)
0.7	−233 (6)	−101 (6)	3 (10)	51 (9)	81 (12)	122 (10)	128 (14)	167 (11)
1	−196 (7)	−1 (7)	107 (13)	183 (12)	214 (16)	277 (13)	280 (17)	338 (15)
Change in soil N stocks (kg N ha^{-1} yr^{-1})								
0	−26 (0.2)	−24 (0.2)	−20 (0.2)	−19 (0.2)	−18 (0.3)	−16 (0.3)	−16 (0.5)	−14 (0.5)
0.3	−24 (0.2)	−19 (0.2)	−14 (0.2)	−11 (0.2)	−9 (0.3)	−7 (0.4)	−6 (0.5)	−3 (0.5)
0.7	−21 (0.2)	−11 (0.2)	−7 (0.3)	−2 (0.3)	0 (0.4)	5 (0.4)	5 (0.5)	9 (0.6)
1	−20 (0.2)	−5 (0.3)	−3 (0.4)	6 (0.4)	7 (0.4)	14 (0.5)	13 (0.6)	20 (0.7)

Note. The standard error of the mean (SEM) is given in brackets.

produce the same quantity of yields compared to the intercropping system (Figure 4c). At fertilizer application levels >50 kg N ha^{-1} yr^{-1} no trend in LER was observed.

3.3.2. Effects of Intercropping, Residue Management and Fertilizer Application Rates on Soil Organic C and Soil N Stocks

The development of soil organic C stocks is important for assessing the sustainability of agricultural management practices. Our simulation suggests that changes in SOC stocks were highly dependent on residue return, with 354 kg C ha^{-1} yr^{-1} of soil C increase if residues were fully returned compared to complete residue removal ($p < 0.05$; Table 4) or 0.135 kg soil C gain per kg residue return. Intercropping increased SOC stocks compared to sole maize systems (49 kg C ha^{-1} yr^{-1}; $p < 0.05$; Table 4), with the strongest intercropping effect related to the scenarios of highest residue return and no fertilization addition. For instance, when all residues remained on the field, intercropping compared to sole cropping increased SOC in unfertilized systems by 195 kg C ha^{-1} yr^{-1}, and by only 58 kg C ha^{-1} yr^{-1} in systems receiving 150 kg N ha^{-1} yr^{-1} relative to the case where no residues remain. Residue removal eliminated the intercropping effect, which implies that belowground residues alone could not significantly reduce C losses in intercropping compared to sole maize systems (only 6–10 kg C ha^{-1} yr^{-1}, $p > 0.05$). Fertilizer provides a larger benefit for SOC than intercropping alone at the same level of residue return. Fertilizer application significantly reduced the magnitude of soil C losses by 0.6 kg ha^{-1} yr^{-1} per kg N ($p < 0.05$) due to increased belowground biomass returns and increased net N immobilization at higher fertilizer rates independent of the amount of residue return. If residues were left on the fields, fertilizer additionally reduced SOC losses due to higher aboveground residue returns at higher fertilizer rates, resulting in a total of 2.0 kg C ha^{-1} per

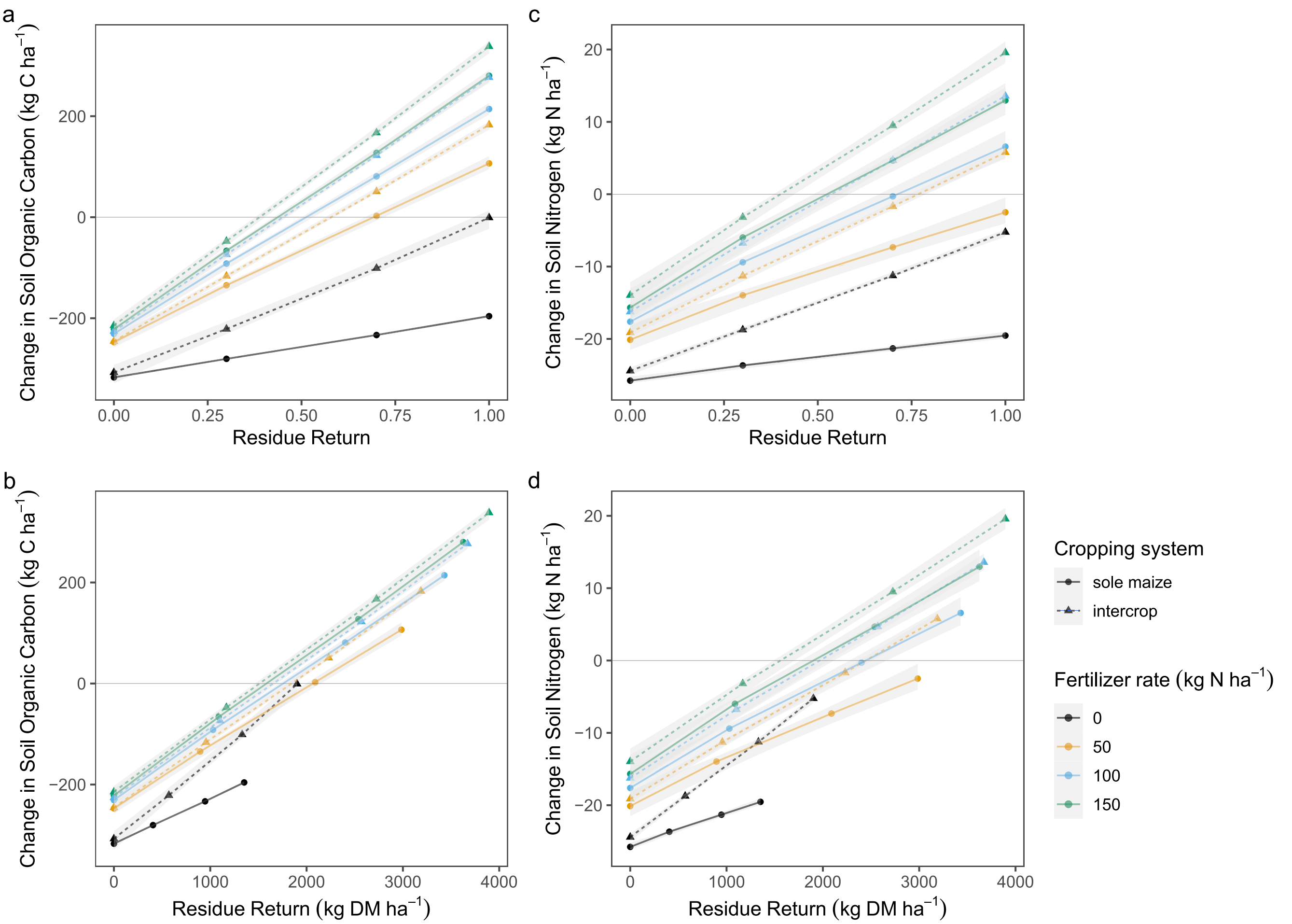

Figure 5. Changes in (a) SOC and (b) soil N (kg ha^{-1} yr^{-1}) comparing sole (solid lines) and intercropping systems (dashed lines) managed with different annual fertilizer rates (color) dependent on different fractions of residue return (*x*-axis). The panels below show the same data of (c) SOC and (d) soil N dependent on absolute residue amount. Gray shading shows the confidence intervals of the regression lines.

kg N fertilizer at 70% and 2.6 kg ha^{-1} per kg N fertilizer at 100% residue return, corresponding to an increase in soil C stocks of 200 and 260 kg per 100 kg N fertilizer per year, respectively.

Roughly 1,500–2000 kg dry residue mass ha^{-1} is needed to maintain SOC stocks, depending on the fertilization level and cropping treatment (Figure 5c). This means that all residues must remain on the field in intercropping systems when no fertilizer is applied and 60% of residues must remain on the field at 50 kg N input (Figure 5a). In contrast, for sole maize systems it is not possible to maintain SOC stocks without fertilizer application, and as much as 70% of residues need to remain on the field to maintain SOC at 50 kg N input (Figure 5a). Thus, intercropping can make a significant contribution to sustaining SOC stocks given that most or all residues are returned to soils (Figure 5a and Table 4) and is of particular importance if no fertilizer is applied. Substantial changes in the slope of the relationship between residue return and soil C or N appear when comparing the unfertilized sole maize and intercropping cases, which is due to the difference in residue quality, with intercropping providing residues of lower C/N ratio and consequently enabling benefits for SOC stocks. Increases in SOC stocks over the 20-year simulation period occurred only in scenarios with a fraction of >1,500–2,000 kg ha^{-1} residues left on the fields, dependent on the N fertilizer application rate (≥50 kg N ha^{-1}; Figure 5).

Soil N mining, the decline in soil N stocks, is a major problem for soil fertility in low input agroecosystems in SSA. In our 20 years' simulations, we observed soil N mining in most scenarios, but soils with intercropped maize systems experienced significantly less N mining compared to the sole maize systems (difference of 5.0 kg N ha^{-1} yr^{-1}; $p < 0.05$; Figure 5c and Table 4). Soil N changes were largely dependent on residue return, which increased soil N stock changes by 23.0 kg N ha^{-1} yr^{-1} compared to complete residue removal (Table 4,

Figure 5c) or by 0.0088 kg N per kg residue DM (Figure 5d). The greatest effect of intercropping on soil N stocks was observed in systems without fertilizer and with high (>50%) residue fractions remaining in the field. For instance, at rates of 0 and 50 kg N, intercropping increased soil N stocks by 14.3 and 8.3 kg N ha^{-1} yr^{-1} respectively, when all residues were left on the field ($p < 0.05$), since biomass additions contributed to the soil N pool. However, the intercropping effect was small for complete residue removal (1.3 and 1.0 kg N ha^{-1} for 0 and 50N respectively; $p < 0.05$). There was no intercropping effect on soil N stocks at fertilizer rates ≥100 N ha^{-1} yr^{-1} ($p > 0.05$). Fertilizer largely affected soil N stocks, with the highest benefits at high residue return rates. N fertilizer application reduced N mining by 0.07 kg ha^{-1} per kg N fertilizer due to higher belowground biomass returns and higher net N immobilization at higher fertilizer rates. If residues are returned to soil, fertilizer indirectly reduces soil N losses via stimulated aboveground biomass growth and subsequent returns. Thus, if this indirect effect is included, N losses are reduced by 0.11 kg N ha^{-1} per kg N fertilizer at 30%, by 0.15 kg N ha^{-1} per kg N fertilizer at 70% and by 0.19 kg ha^{-1} per kg N fertilizer at 100% residue return ($p < 0.05$), which is equivalent to 11–19 kg soil N stock increase per 100 kg N fertilizer.

Achieving balanced N stocks requires both sufficient residues and N fertilizer inputs, while intercropping practices can compensate to some extent for the lack of residue or N fertilizer input. Regardless of the cropping system, severe soil N mining was observed under complete residue removal, indicating that intercropping alone cannot maintain soil N stocks (Figure 5c). Maintaining soil N stocks required at least 35 kg N ha^{-1} yr^{-1} mineral fertilizer N input in intercropping systems, while sole maize systems required at least 70 kg N ha^{-1} yr^{-1} (Figure 5c) at full residue return. At 50% residue return, intercropping systems required as much as 120 kg N and sole maize systems 150 kg N to maintain soil N stocks. For lower residue return fractions, the fertilizer requirements to achieve balanced N stocks were higher, so fertilizer inputs were less effective and reduced soil N losses to a smaller extent per additional unit fertilizer. Increased fertilizer use is associated with higher nitrate losses as well as higher gaseous N losses (N_2O, NH_3 and other N compounds), whereas residue returns and intercropping mitigate environmental N losses (data not shown).

Reflecting the moderate differences between C and N stock changes, the C/N ratio of soils narrowed over 20 years below 50% residue return and widened slightly at high residue return ($p < 0.05$). While the C/N ratio increased with residue return, it only increased to a minor extent with fertilization (0–150 N has roughly half of the effect size compared to 0%–100% residues). Significant intercropping effects on the soil C/N ratio appear in the form of widening the C/N ratio only at 0N with residue returns.

4. Discussion

In this study, we showed that the implementation of intercropping in the biogeochemical model LandscapeDNDC provides a means for simulating yield benefits and total plant N uptake of intercropping systems. Such a model feature is needed to assess the long-term effects of intercropping on yields and soil C and N budgets in cropping systems and to evaluate potential impacts on soil fertility and environmental N losses. LandscapeDNDC captures the trend of slightly lower maize yields in intercropping as compared to sole cropping systems (Tables S2 and S3 in Supporting Information S1), while total yields (legume plus maize) exceed those of sole maize yields (Figures 2 and 3). Since the scaled yields per fertilizer input were higher in intercropping than in sole cropping systems, intercropping can be seen as a sustainable intensification strategy with respect to yields. Intercropping showed advantages in long-term yield development if fertilizer input is low (Figure 4). Moreover, our findings reveal that intercropping leads to higher SOC and soil N stocks relative to sole maize systems (Figure 5). This effect is particularly pronounced in systems characterized by no fertilizer application and high rates of residue return, highlighting the potential of intercropping to help maintain soil fertility in low-input subsistence farming systems. Our model results underscore that legumes can make a substantial contribution to sustaining productivity and soil fertility in low-input smallholder farming systems (Giller, 2001; Sanginga, 2003). However, we show that the benefits of legumes in intercropping systems regarding yield and soil fertility depend crucially on maintaining sufficient above- and belowground crop residues in the fields. Fertilizer helps maintain soil C and N independent of the amount of residue returned, but fertilizer benefits increase with increased residue returns.

4.1. Model Performance

The calibrated LandscapeDNDC model was able to reproduce the measured grain yields of the different validation sites and cropping systems with a relative root mean square error of 21%. This performance of

LandscapeDNDC in this study is consistent with the performance in other calibration studies on sole cropping systems. Since the performance of maize-legume intercropping in SSA has not been previously reported, we compare it with studies using biogeochemical models for sole maize systems and sole soybean. For instance, DayCent predictions of sole crop grain yields in the US for maize resulted in r^2 of 0.54, bias of 0.07 t ha^{-1} and RMSE of 1.35 t ha^{-1} (Zhang et al., 2020), while our study resulted in r^2 of 0.55, bias of 0.34 t ha^{-1} and RMSE of 1.16 t ha^{-1}, when considering sole and intercropped maize. For soybean, DayCent showed slightly better results with r^2 of 0.54, bias of 0.05 t ha^{-1} and RMSE of 0.4 t ha^{-1}, compared to our study's soybean with r^2 of 0.11, bias 0.34 t ha^{-1} and RMSE of 0.67 t ha^{-1}, which was due to a low variability of yields among sites in our study. In a model ensemble study by Falconnier et al. (2020), multiple crop models were calibrated for maize yields under low nitrogen input conditions in SSA using various variables such as grain yield, plant biomass, plant N in biomass, LAI (Falconnier et al., 2020). Average rRMSE across the crop models was 26% for sole maize grain yields, with individual models ranging between 8% and 82% rRMSE, compared to 48% in our study. LandscapeDNDC rRMSE performance was within typical ranges for all other variables, for example, 61% for total aboveground maize biomass compared to other crop model ranging between 17% and 58%; for the maximum LAI 55% compared to 6%–79%, as well as total aboveground plant N 67% compared to 7%–78% in other models after full calibration (Falconnier et al., 2020). Falconnier et al. (2020) reported that model simulations of low input, low yielding systems are less accurate compared to those of fertilizer-driven high-input situations since they fully rely heavily on adequately simulated soil N mineralization dynamics. This challenge of accurately representing low-input systems could partly explain the uncertainly observed in our study for those sites with low or no fertilizer N inputs. However, in our study, performances at high and low-input sites were similar. Main limitations in model performance can be attributed to considerable input uncertainty, for instance in climate and in particular precipitation data, which is besides N the main limiting factor regarding crop growth. Inter-annual variability at site level was not always represented well in the gridded climate data set we used here, and site-specific climate may largely impact the result, particularly at sites of low yield stability. Nevertheless, the similar values of model performance at independent validation sites compared to calibration sites indicate that the model is not overfitted and well transferable to other sites.

The sites have on average relatively low maize yields (average 2085 t ha^{-1}), which result from the calibration of the region-specific varieties under water limitation at sites receiving low mean annual precipitation. The ability of the calibrated parameter sets to simulate situations beyond the environmental conditions present in the calibration may be limited. Thus, a simulation of the potential productivity of the calibrated varieties under irrigation or at high rainfall conditions would potentially lead to an underestimation of productivity. Yield limitations at the experimental sites might also be due to micronutrient deficiency, unreported weeds, pests, or disease. Furthermore, the yield potentials of the cultivars grown at the sites, which lie below the yield potentials of the hybrid varieties available in SSA, are a limiting factor to productivity in our simulations.

In addition to accurately representing sole crop systems, we successfully simulated intercropping of maize with different legume crops using LandscapeDNDC. To our knowledge, there are no comparable validation studies presented in the previous literature for maize-legume systems under low N input conditions. While many studies focus on yield and aboveground biomass, LandscapeDNDC was successfully validated beyond these parameters, specifically aiming to represent the main plant N pools and processes in intercropping systems, such as N in aboveground biomass and N_2 fixed via legumes. This aspect of the validation exercise is crucial for assessing the impact of intercropping on C and N cycling and for assessing long-term effects on soil fertility and yields.

Previous modeling studies for intercropping systems range from empirical model improvements to mimic differences in N access to attempts to incorporate the effects of improved spatial representation of crop mixtures. For maize-soybean intercropping in China, a simplified empirical scheme was applied to better represent the belowground competition for N of the standard DNDC crop module (Fung et al., 2019). However, maize and soybean sole yields in that study were largely overestimated by a factor of 2.1 and 1.7, respectively, while intercropping yields were not validated. In a more process-based approach, like in this study with LandscapeDNDC, models simulate intercrops assuming a mixed canopy with a horizontally homogeneous LAI distribution and shared soil layers among different crop species. This principle is valid for mixed intercropping systems as assumed in our study, and we showed that the simplification of assuming mixed systems works well within the scope of our study. There are examples in the literature that go beyond the mixed canopy assumption, specifically targeting an advanced representation of light competition in strip and row intercropping systems (Knörzer, Lawes, et al., 2011). A shading approach used with DSSAT (based on CERES-maize and CERES-wheat) adequately reflected the shading effect on grain yields and biomass in strip intercropping as well as in relay intercropping (Knörzer, Grözinger, et al., 2011). In this approach, the authors modified the solar radiation input for intercropped species by calculating shading in dependence of neighboring plant height. However, these up to now were only developed at site-scale and our limitation in data availability does not allow conducting this approach here. Nevertheless, such an approach could be seen as a further step desirable also for regional parametrizations. In a contrasting approach, Wu et al. (2021) tackled the challenge to model maize-soy strip intercropping in APSIM by adjusting parameters separately for sole and intercropping system configuration, thus deviating from the principle of using the same crop parameters for sole and intercrops. Arguing with the theoretical principles of process-based modeling, we and others (Knörzer, Grözinger, et al., 2011) believe that it is essential to use a common parameter set that applies to both sole and intercrops. With this validation, LandscapeDNDC is prepared for farm and regional scale assessments of maize-legume intercropping.

4.2. Long-Term Effects of Intercropping on Yields and Soil C and N Stocks

In our study, the greatest benefits of intercropping were simulated for low-N-input systems, in line with the meta-analysis of Bedoussac et al. (2015), suggesting that intercropping is particularly suitable for field situations with low-N availability. Furthermore, our simulations showed higher N concentration (and thus protein concentration) in intercropped grain maize compared to sole cropped maize, particularly at low N fertilizer rates. This aligns well with findings from the meta-analysis of Bedoussac et al. (2015), which showed that intercropping increased cereal protein concentrations in European organic farming systems. This higher cereal protein concentration in intercropping systems results from the low competitiveness of legumes for mineral N combined with the lower intercropped cereal yield compared with the sole crop yield.

Our simulations indicate a decline in yields for unfertilized sole maize systems over 20 years in all residue scenarios. In contrast, intercropping systems showed a decrease in yields only when no residues were left in the field. When combined with full residue return, maize-legume intercropping showed the potential to prevent significant yield losses over 20-year period even at 0N fertilizer input. The importance of residue return was underlined previously by Madsen et al. (2021), who showed that incorporating legume residues soon after harvest greatly increased the likelihood of smallholder farmers to be food secure. For systems without N fertilizer inputs, significant intercropping effects on yields highlight the importance of intercropping when fertilizers are not affordable. The magnitude of the intercropping effect on yields at 0N corresponds to a fertilizer application of ∼10–35 kg N, depending on residue return. The results of our scenario modeling suggest that while intercropping and residue returns can contribute to increased yields, fertilizer application is the dominant factor that affects productivity (Figure 4). However, fertilizer use in SSA is restricted by costs and availability. It can be unprofitable for smallholder farmers to increase fertilizer amounts if fertilizer response rates are low, that is, due to (a) low and sporadic precipitation, (b) too late delivery and application of fertilizer, (c) lack of appropriate management and (d) lack of timely weeding (Ricker-Gilbert, 2020; Vanlauwe et al., 2011).

However, in addition to the above, poor soil fertility was identified to be the major constraint for crop productivity in smallholder farming in SSA (Vanlauwe et al., 2014; Vanlauwe & Giller, 2006; Vitousek et al., 2009). Declines in soil organic C stocks negatively affect soil quality by (a) reducing the water-holding capacity of soils, (b) reducing their ability to store nutrients and (c) degrading soil structural properties. Long-term measurements comparing soil C and N changes in intercropping systems are not available for SSA; thus, we used our biogeochemical model to assess the long-term effects of intercropping on productivity and soil C and N dynamics in SSA. It needs to be acknowledged that long term validation on SOC and N in African systems is missing, which is a well-known problem that increases the uncertainty of the results. Ideally, long-term experimental trials on the effect of intercropping on SOC stocks in Africa are required to ensure the best-possible validation. However, since the underlying biogeochemical processes were widely evaluated, we assume that the model still captures the dynamics of SOC correctly and believe that it is one of the best available tools currently available to project management impacts on SOC developments. To our knowledge, this is the first study to assess the long-term effects of fertilizer and crop residue management on C and N stock dynamics of maize-legume intercropping systems across different bioregions in SSA. Our findings support the beneficial effects of intercropping on soil C and N stocks, but we also found that these effects are highly dependent on the amount of residue returned as the intercropping of legumes alone is not sufficient to maintain soil C and N stocks. Regardless of whether a sole maize or intercropping system was cultivated, all sites experienced soil N mining and SOC losses under standard management (30% of stover left on the fields) over the 20 years simulation period.

Our findings suggest that changes in soil C and N stocks in sole and intercropping systems are primarily influenced by residue management. Since intercropping systems produce higher amounts of aboveground and belowground residues per unit area than monocropping systems, the residue effect on SOC and soil N is stronger in intercropping systems. Experimental evidence confirms that residue returns significantly increase SOC and that the effect is stronger in maize-soybean intercropping compared to sole maize systems (Bichel et al., 2016). In our study, intercropping dominantly affects SOC and soil N in systems with low (0–50 kg N ha^{-1}) fertilizer input and/or with high residue return (Figure 5). When no fertilizer is applied, implementing intercropping and maximizing residue retention minimizes losses of SOC (−1 compared to −196 kg C ha^{-1}, Table 4) and soil N (−5 compared to −25 kg N ha^{-1}, Table 4). At higher fertilizer rates (100–150 kg N ha^{-1}), the effect of intercropping on SOC and soil N is significant when a high fraction of residues is retained but disappears at low residue returns.

Changes in SOC and total N are hardly detectable in short-term experiments due to the relatively small changes in SOC and soil N compared with large stocks. For instance, Myaka et al. (2006) and Adu-Gyamfi et al. (2007) found no effect on soil N stocks after two seasons of pigeon pea intercropping with maize. To date, only limited long-term measurements are available for assessing the small changes in SOC and N stocks experimentally. However, in long-term experiments conducted by Li et al. (2021) in northwest China, intercropping significantly increased SOC by 11.6% and TN by 9.1% over 10 years at the Hongsibu site (75 and 150 kg N fertilizer ha^{-1} yr^{-1}). In contrast, SOC and TN did not change over 16 years at the intensively fertilized Baiyun site (225 kg N fertilizer ha^{-1} yr^{-1}). However, an earlier publication of the data from the Baiyun experimental site over 7 years (Cong et al., 2015) had previously indicated a gain in SOC by the intercropping management. This highlights the need for more long-term observations to adequately assess the effect of intercropping on SOC and soil N stocks for different soils and environmental conditions, as well as the necessity to use validated models to help identify long-term trends. In our model simulations, maximum changes in SOC in intercropped systems were 4.8% C over 10 years at 150 kg N fertilizer and full residue return, while N changes in this scenario were 3.4%, indicating that our estimates of SOM gain due to intercropping (averaged across all sites) might be rather conservative. Further, in our scenarios, we simulated soil N stock changes ranging from −26 to +20 kg N ha^{-1} yr^{-1} (Table 4), while a review on plot-scale N balances for agricultural fields in Africa (Cobo et al., 2010) reported higher median soil N losses of 41 kg N ha^{-1} yr^{-1} , with half of the plots showing losses between 4 and 55 kg N ha^{-1} yr^{-1}. The wide range in N balances across plots in this review indicated large spatial variations (−140 to +114 kg N ha^{-1} yr^{-1}). Although these data included different agroecosystems and are not specific for maize cultivation, they provide evidence that our model predicts rather conservative soil N losses that are within plausible ranges across systems in SSA.

4.3. Implications and Limitations

The results of our scenario modeling suggest that using legume intercropping together with an increase in residue return is a viable practice to minimize losses of SOC and SON in cropping systems, which is pertinent for maintaining or restoring soil fertility. Regarding the benefits of improved soil fertility, it is recommended to leave as much aboveground residue on the field as possible, ideally in combination with intercropping. However, there are several potential barriers to adopting such a management practice. Our simulations suggest that a positive yield response to residue additions occurs only after several (∼3) years (Figure 4). The lack of a yield response to a management adoption for several years might be one of the main barriers to adoption. Another barrier is the maize yield penalty, which occurs at intercropping (see Figures S2 and S3 in Supporting Information S1), reducing maize yields by 12% on average in intercropped compared to sole maize systems. However, the choice of intercrop can minimize the yield penalty, that is, using bean as intercrop reduced maize yields by less than 5% at our sites. Nevertheless, average intercropping grain yields at our intercropping sites exceed sole maize yields by 16% measured (by 13% simulated) unlike results from the global meta-analysis (Li et al., 2023) showing that intercropping grain yields were 4% lower compared to the best-performing sole crop. A further barrier is that in smallholder agricultural systems residues are widely used for other purposes such as dry season livestock feed in mixed crop-livestock systems but also for generating additional income as fuel or construction material (Valbuena et al., 2015). With growing population density, crop residues have become a limited resource in mixed crop-livestock farms in the developing world (Herrero et al., 2010), creating a conflict between using residues for soil fertility and long-term productivity and meeting other priorities such as animal feeding. The decisions of the farmers regarding residue use depend on the demand for biomass, and are determined by the access to and affordability of alternative biomass resources (Valbuena et al., 2015). Current practices in residue management can vary considerably between regions, but the most common use among smallholder farmers is as a dry season feed resource (Valbuena et al., 2015). Potential side effects of high residue return such as pests and diseases need to be considered although these aspects were not addressed in our study. Additionally, we did not address the question of the optimal application method of residues, such as whether to incorporate them into the soil after grain harvest or leave them on the surface, as assumed in this study. Furthermore, the technical expertise needed for the proper application of intercropping practices can be another barrier to adopting intercropping in smallholder farming or a factor limiting the intercropping effect (Himmelstein et al., 2017). The intercropping effect has been found to be higher if herbicides are available (Himmelstein et al., 2017), since manual or mechanized weeding is often difficult due to spatial arrangements in intercropping systems. Additionally, sub-optimal legume growth due to lacking *Rhizobium* inoculation, low soil phosphorus levels, or other limiting factors can undermine legumes' growth potential (Himmelstein et al., 2017).

Our N budgets represent an average across all simulated fields. However, in resource-limited smallholder agriculture not all fields are managed the same, as fields can have positive nutrient balances, often the ones in closer distance to the farm (Cobo et al., 2010; Vanlauwe et al., 2015; Zingore et al., 2007). Therefore, the quantification of optimal N inputs and management recommendations for residue return need to be assessed field-specific and in the context of overall farm management.

5. Conclusion and Outlook

The long-term scenario simulations conducted in this study highlight the positive contribution of intercropping to maintaining soil C and N stocks, which support food security. Our results suggest that intercropping, coupled with high residue return, can help maintain stable yields, prevent SOC losses and minimize or prevent soil N mining at low fertilizer N inputs. However, successful implementation of intercropping requires farmers' expertise. Additionally, the residues needed for high residue return may be required for other purposes, and yield benefits due to residue returns may emerge only after several years, putting several challenges on this strategy. If these challenges can be addressed locally, maize-legume intercropping combined with residue returns can be a valuable strategy to contribute to improved food security, with benefits to yields and soil fertility even if no additional mineral fertilizer is available. To further strengthen our understanding and improve the quantification of the effects, it is crucial to complement and constrain further modeling approaches with long-term observational data. A combination of modeling and experimental approaches is needed to refine our knowledge and develop targeted strategies to maximize the benefits of intercropping for smallholder farmers in the region.

Data Availability Statement

Data archiving is provided via the KITopen repository (K. Fuchs, 2024).

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