Biomass flows in an agro-pastoral village in West-Africa: who benefits from crop residue mulching?

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Abstract

In West Africa, new management practices such as conservation agriculture with crop residue mulching can improve crop yields for individual farmers. However, in a context of complex social interactions between farmers, the introduction of such practices can also lead to conflicts between private interests and communal use of resources, for example the free-grazing of crop residues. The objective of this paper was to assess ex-ante the impacts of the practice of crop residue mulching on crop productivity in a village of central Burkina Faso using an agent-based model (AMBAWA) that simulates the flows of biomass and nutrients between crop and livestock systems at the village scale. The model considers the interactions between four types of farmers that were identified in the study site: subsistence-oriented crop farmers, market-oriented crop farmers, agro-pastoralists and pastoralists. The model simulated increased cattle migration outside the village due to increased crop residue scarcity during the dry season with increased proportions of cropland under the practice of conservation agriculture, decreasing the manure availability at village scale. Consequently, the assumed direct yield increases as a result of mulching due to soil moisture conservation did not compensate for the yield losses resulting from lesser amounts of manure available. This effect was felt most strongly by farmers who own relatively large numbers of cattle (agro-pastoralists and pastoralists). The total maize production at village level depended more on the proportion of cropping land that was available for grazing by cattle, and thus not mulched, than on a possible direct effect of mulching on yield per se. The AMBAWA model can support discussion among stakeholders (farmers, traditional and administrative authorities) who are involved in the private and communal management of crop residues and other biomass resources, in order to co-design effective arrangements and practices for their sustainable use.

Keywords:

Agent-based model, agro-pastoral systems, conservation agriculture, crop residues, village, mulching.

1 Introduction

In the agro-pastoral regions of West Africa, crop residues and livestock play an important role in soil fertility management, especially in the context of a growing disappearance of land fallow practices (Bationo et al., 2007; Manlay et al., 2004). Traditional by-laws regulating the communal use of natural resources prescribe the grazing of crop residues by free-roaming village or transhumant livestock during the dry season. To respond to the increased food demand in the rural and urban areas, new crop management practices based on recycling of crop residues as compost or their use as mulch in fields are promoted by international and national research and development programs (Nafi et al., 2020). These practices can potentially improve crop yields for individual farmers but can also lead to conflicts between private interests (i.e. soil fertility maintenance of fields by individual farmers) and communal agreements (i.e. feeding the village herd during the dry season) (Andrieu et al., 2015).

Mulching with crop residues is one of the principles of conservation agriculture, a crop management practice that entails minimum or no soil disturbance, soil cover with living or dead plant material (mulch) and crop diversification (Hobbs et al., 2008). However, in the absence of crop field fencing, maintaining a year-round cover of crop residues, protected from free-roaming cattle, becomes a challenge for farmers (Giller et al, 2009).

Some authors have analyzed the specific trade-offs that can occur between livestock and cropping systems after the introduction of crop residue mulching on smallholder farms (Naudin et al., 2011; Andriarimalala et al., 2013; Rusinamhodzi et al., 2015). However, such trade-offs must also be analyzed at the village scale because of the direct and indirect interactions between farmers and farm types that affect the individual farming systems. In general, integrative analytical modelling tools can help to explore the consequences of the introduction of new crop management practices on organic and mineral resource flows, soil fertility and crop yields at the field, farm, and village scales, in a context of complex social interactions between local actors (Rufino et al., 2011). Agent-based models have been shown to be effective tools to capture such interactions between farmers, and their effects on the individual farms and the agricultural system at a higher scale (village, landscape, region) (Saqalli et al., 2011; Happe et al., 2011; Valbuena et al., 2010).

In the context of Africa, agent-based models have been particularly applied to analyze the interactions between human dynamics (immigration, emigration, and population growth) and the environment (e.g. soil quality) (Bah et al., 2006; Belem et al., 2011; Grinblat et al., 2015), and to study the adaptations of farmers to climate change (Wossen and Berger, 2015; Amadou et al., 2018; Belem et al., 2018). Besides, this type of models has also been used to quantify the impact of agricultural expansion on livestock production and nutrient cycling (Grillot et al, 2018), and to assess the effect of policy interventions on the adoption of conservation agriculture (Bell et al., 2016) or on the socio-ecological resilience of communal rangeland systems (Rasch et al., 2017). In some of these studies, both the cropping and livestock systems were considered, the livestock system often being seen as a source of capital and social resilience. However, so far, no studies in sub-Saharan Africa have explored the effects of the introduction of a new agricultural technology on organic resource exchanges between farmers, and their consequences for crop productivity.

The objective of this paper is to assess the effects of crop residue management (mulching versus cattle feeding) on crop productivity in a village of central Burkina Faso by means of an agent-based model that simulates the flows of biomass and nutrients between crop and livestock systems at the field, farm, and village scales. For this purpose, we developed the Agent-based Model of Biomass flows in Agro-pastoral regions of West Africa (AMBAWA) that enables to explore different scenarios of crop residue mulching on crop productivity at the field, farm, and village scales. We first describe the farms in the study region using a farm typology, and the inflows and outflows of organic and mineral resources at the field and farm scales for the different farm types. We then present the AMBAWA model and the scenario model runs with their results. Next, we discuss the implications of these results for crop residue and cattle feeding management. Lastly, we give a concluding vision on the usefulness of AMBAWA for assessing the effect of management strategies on farm productivity and sustainability in the agro-pastoral systems of West Africa.

2 Materials and methods

The study consisted of three phases: 1) a typology of existing farms; 2) a quantification of inflows and outflows of farm resources at the field and farm scales for the farm types identified in the previous phase; and 3) the development of the AMBAWA model and its use for scenario analysis of farm management on crop productivity. Details on phases 1) and 2) can be found in Diarisso et al. (2015a). Here we give a brief overview of the farm typology and the resource flows, along with a description of the model and its use in the context of the study.

2.1 Study area and farming systems

2.1.1 Study area

The study was carried out in Koumbia (3°41'15” W; 11°14'47” N), a village situated in the cotton/maize-growing region of Burkina Faso, representative of the Sudanian agro-ecological zone. Population density is close to 60 inhabitants km^{-2}. This region is the breadbasket of the country where at the same time the highest animal stocking rates occur. The rainfall pattern is unimodal with annual rainfall between 800 and 1100 mm. The rainy season (between May and October) is when crops are grown and livestock graze on the savannah rangelands. The dry season can be divided into two periods: a period known as ‘cold’ with an average temperature of 27°C (October–February) when crops are harvested and communal grazing begins, with cereal crop residues left in the fields being the main source of fodder, and a hot period (March – May) with an average temperature of 31°C, when the crop residues on the fields are becoming strained. In this period of the year, livestock feeds on the cereal crop residues that were stocked on the farms, and on the biomass remaining in the savannah rangelands, or leave the village in search of rangelands elsewhere. The soils in the region are mainly Luvisols and Lixisols (FAO World Reference Base for Soil Resources). Currently, most agricultural production systems are mixed crop-livestock farms that employ animal traction and use manure for soil fertility management.

2.1.2 Typology of farming systems and farm resource flows

Individual household surveys to characterize the farms were conducted between September and October 2012 in the village of Koumbia. Fifty-three farms were randomly selected. A questionnaire was implemented to collect information on socioeconomic aspects of the households (size of farm, labour, assets, types of crop and livestock systems, market access, off-farm activities). The collected data were subsequently used to build a typology of farms based on structural farm characteristics (total farm area, cash crop (cotton) area, labour availability, cattle number, percentage of off-farm activities). Principal component analysis and ascendant hierarchical clustering methods (Alvarez et al., 2018) were used to discriminate and to reassemble farms into four homogeneous groups based on their similarity according to structural farm variables. The following four farm types were identified: subsistence-oriented crop farmers (SO), market-oriented crop farmers (MO), agro-pastoralists (AP) and pastoralists (PO) (Diarisso et al., 2015a) (Table 1).

Table 1: Main characteristics of the four types of farms identified in Koumbia

Type	SO	MO	AP	PA
Total area (ha)	4.5	10	7.8	6.9
Maize area (ha)	2.4	3.7	3.1	3.1
Cotton area (ha)	1.8	5.9	4.5	1.6
Total TLU	4.3	6.7	17	58
Cattle (number)	4.7	9.3	24	80
Small ruminants (number)	11	2	1.7	20
Off-farm activities (% of total household activities)	15	8	10	12
Family labor (number of persons)	4.5	7.0	12	13
Proportion of sampled farms (%)	44	26	17	13

SO: subsistence-oriented farmers; MO: market-oriented farmers; AP: agro-pastoralist; PA: pastoralists; TLU: tropical livestock unit

The subsistence-oriented farms are characterized by low resource endowments; maize grain production is exclusively used for own consumption. They have a small herd and small ruminants represent a relatively high proportion (25%) of the total tropical livestock units (TLU) on the farm. Off-farm activities (masonry and trading activities) are a relatively important activity for this farm type, representing on average 15% of the total household activities. The market-oriented farms have medium resource endowments. Cotton is the main crop, grown under contract farming with the semi-private SOFITEX (Société Burkinabè des Fibres Textiles) company. These farms sell also part of their maize production on local markets. Agro-pastoralists were previously market-oriented farmers who built up a relatively large herd of cattle with the income generated from cotton production. The fourth type of farmers represent Fulani pastoralists. In the past these farmers were nomadic, but they became sedentary in recent decades and began growing crops. Livestock production is clearly the main activity for this group of farmers.

Three representative farms were selected from each type as case studies for in-depth analysis of crop and soil management decisions, soil properties and crop yields. All the organic and mineral resource flows on these farms were quantified at three levels: the farm, the subsystems of the farm, and the fields of the farm. The resource flow diagrams were elaborated and discussed with the farmers of each farm type. The results are described in detail in Diarisso et al. (2015a).

2.2 Presentation of the AMBAWA model

We used the Common-pool Resources and Multi-Agent Simulations -CORMAS- platform (Bommel et al, 2016) to implement the AMBAWA model. The source code and a complete, detailed model description, following the ODD (Overview, Design concepts, Details) protocol (Grimm et al. 2006, 2010) is provided at https://www.comses.net/codebases/4808/releases/1.2.0/. According to recent recommendations made by the proponents of this protocol (Grimm et al., 2020), we provide here a summarized version.

The basic idea underlying the model is to explore the effects of resource flows (organic and mineral fertilizers, crop residues, manure) between farms, crop and livestock systems and crop fields on crop productivity in the agro-pastoral areas of West Africa. We considered the village of Koumbia as a situation to inspire the creation of a stylized model, capturing the main features of the agro-ecosystem rather than providing a realistic representation. Consequently, significant simplifications guided the design of the model. For instance, it includes only the maize crop since it is the most cropped cereal in the study area and its residues are the major source of fodder for livestock (Andrieu et al., 2015). The overall purpose of the model is to compare the effects of different scenarios of crop residue management (mulching versus cattle feeding) on crop productivity at the field, farm, and village scales. To consider our model realistic enough for its purpose, we use quantitative patterns of manure and crop yield changes over time, as well as the date on which animals leave the territory due to a lack of fodder.

The model includes the following entities: farms, cattle, square grid cells of 1 ha, and maize. The state variables characterizing these entities are listed in Table 2. Cells are i) agricultural fields characterized by a soil fertility level and covered either by a maize crop or by a fallow; ii) parts of a rangeland area or iii) structural elements of the village (homes of sedentary villagers, pastoralist encampments, watercourses, protected areas, roads). The four types of farm considered are: i) SO: subsistence-oriented crop farmers; ii) MO: market-oriented crop farmers; iii) AP: agro-pastoralists; and iv) PA: pastoralists. Each farm decides the use of mineral and organic fertilizers to the maize crop and the utilization of maize harvest residues for fodder or soil fertility management. Each head of cattle has a daily fodder need and a daily production of faeces. Cattle are grouped in herds whose location (in rangeland, agricultural fields or away from the village) is decided by the farm that holds them.

Entity	State variable / parameter	Farm type	Value	Unit	Source

Table 2: List of state variables for each entity considered in the AMBAWA model)

Farm	Farm size	SO	4	ha farm^{-1}	Diarisso et al. 2015a
		MO	10		
		AP	8		
		PA	7		
	Harvest of maize stalks	SO	31	% of total production	Diarisso et al. 2015a
		MO	29		
		AP	54		
		PA	46		
	Cattle herd size (min-max)	SO	2-5	TLU farm^{-1}	Diarisso et al. 2015a
		MO	4-8		
		AP	12-20		
		PA	50-60		
	Use of organic N fertilizer (first season, then simulated by the model)	SO	3	kg N ha^{-1}	Diarisso et al. 2015a
		MO	12		
		AP	13		
		PA	39		
	Use of mineral N fertilizer (all seasons)	SO	51	kg N ha^{-1}	Diarisso et al. 2015a
		MO	45		
		AP	31		
		PA	45		
	Grain stock	all 4 types	0	kg farm^{-1}	
	Straw stock	all 4 types	0	kg farm^{-1}	
	Manure in rangeland park	AP & PA	0	kg farm^{-1}	
	Manure in corral	all 4 types	0	kg farm^{-1}	
Agricultural field	Manure deposited (initial value)		0	kg farm^{-1}	
	N balance (initial value)		0	kg farm^{-1}	
	Fertility (initial value)		1		
	Straw residue level (initial value)		0	kg farm^{-1}	
Maize	Basal yield (without fertilization)		400	kg ha^{-1}	Andrieu et al., 2015
	Ratio of grain over the total amount of biomass produced		0.416		Observation from on-station trials
	N concentration in grain		2	%	Andrieu et al., 2015
	N concentration in straw		1	%	Andrieu et al., 2015
	N agronomic efficiency		14	kg ha^{-1} kg N^{-1}	Andrieu et al., 2015
	Yield (calculated by the model)			kg ha^{-1}	
Cattle	Minimal fodder consumption rate		4.5	kg of dry matter TLU^{-1}day^{-1}	Assouma et al., 2018
	Maximal fodder consumption rate		6.25	kg of dry matter TLU^{-1} day^{-1}	Defoer et al., 1998
	Ratio of faeces produced during the night		0.7	-	Rufino et al., 2006
	Faeces to organic N conversion rate		0.0114	kg of organic N kg^{-1} of faeces	Observation from on-station trials
	Maximal daily faeces production		2.8	kg of faeces day^{-1}	Landais & Lhoste, 1993 Defoer et al., 1998)
	Satiety (daily coverage of fodder needs)		1	-	

SO: subsistence-oriented crop farmers; MO: market-oriented crop farmers; AP: agro-pastoralists; PA: pastoralists; N: nitrogen; TLU: tropical livestock unit

As for the spatial and temporal resolution and extent: a time step in AMBAWA is a half-day to represent the succession of days (during which cattle are feeding in rangeland or agricultural fields) and nights (during which cattle are kept in corrals). Decisions on maize production are biannual (at the start and end of the maize growing season) (see Figure 1). The virtual village is made of 30x30 cells of 1 ha.

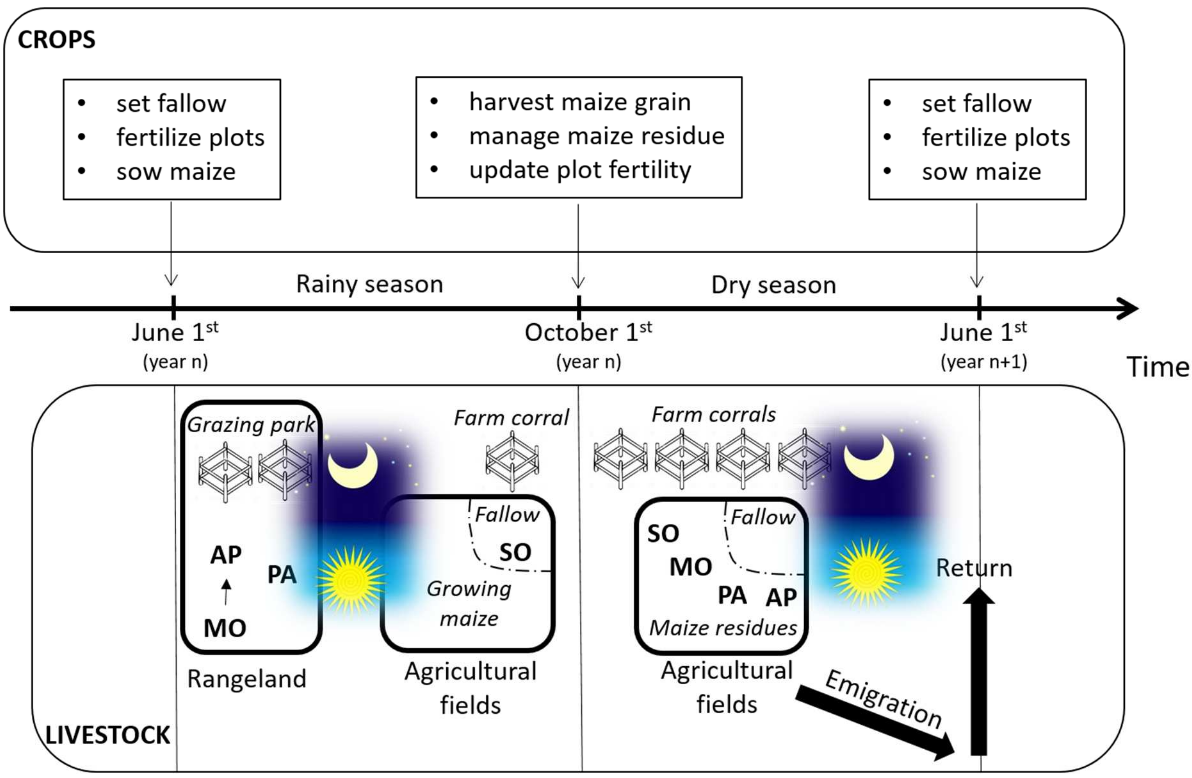

Figure 1: Overview of cropping schedule and livestock mobility and feeding throughout the year in the AMBAWA model (half-day time-step).

SO: subsistence-oriented crop farmers; MO: market-oriented crop farmers; AP: agro-pastoralists; PA: pastoralists;

The most important processes simulated by the model are listed and explained below.

The location of cattle feeding and production of faeces is processed every half-day according to seasonal patterns specific to each farm type (see Figure 1). During the day, animals feed either in rangeland areas (market-oriented farmers, agro-pastoralists and pastoralists during the rainy season) or in agricultural fields (in fallow fields for animals belonging to subsistence-oriented farmers during the rainy season), and in maize fields after harvest for all cattle during the dry season. Animal faeces produced directly in a field contribute to its organic fertilization. Fodder biomass (from rangelands and fallow land) is assumed to be sufficient during the rainy season whereas during the dry season, when feeding on the maize residues, the satiety of animals is calculated based on the quantity of biomass eaten. From the first day when their satiety goes below a threshold, animals emigrate (exit the simulation) until the beginning of the next rainy season. This represents the practice of transhumance in search for fodder outside the village area. At night, during the time they are present in the simulation, animals are corralled in parks where their faeces is collected to fertilize the maize crops. Both agro-pastoralists (with their own cattle plus the one entrusted by market-oriented farmers) and pastoralists will use parkland manure collected during the rainy season as fertilizer on their fields during the next cropping season, even if its quality is affected by this long storage period (see section 4.2). During the dry season, manure is collected in farm corrals at night by each farm and also used as organic fertilizer on the individual maize fields.

The use mineral and organic fertilizers to the maize crop is decided by each farm at sowing time (June 1st, see Figure 1), mineral fertilizer use remaining constant in time according to observed values form the household surveys (Table 2). The amount of mineral nitrogen applied by the farmer, Min_N, thus depends on the farm type, whereas the amount of organic nitrogen, Org_N is the sum of the manure available and applied by farmer on his field and the quantity directly deposited on that field by grazing animals through their faeces.

The maize grain yield is calculated at harvest (1st of October) as a function of a basal grain yield, soil fertility, mineral nitrogen fertilizer and organic amendments, as follows:

$$GrainYield = (BasalYield \times FertIndex) + \left(\left(Min_N + Org_N\right) \times NAE\right) \quad (eq. 1)$$

$$StrawYield = GrainYield \times \left(\frac{1 - HI}{HI}\right) \quad (eq. 2)$$

BasalYield is the maize grain yield with standard soil fertility (*FertIndex* = 1) and without nitrogen input, *NAE* the agronomic nitrogen-use efficiency of added nitrogen, and *HI* the harvest index of maize, i.e. the ratio of grain production on the total biomass (Table 2 indicates the sources of information used to select parameter values). The fertility level of each cropland field is then updated as follows:

$$FertIndex^{t+1} = FertIndex^{t} + \left(\frac{Min_N + Org_N}{Cupt_N}\right) \quad (eq. 3)$$

$FertIndex$ is a factor that represents the level of soil fertility of the field at time t and t+1, and $Cupt_N$ is the amount of nitrogen taken up by the maize crop that is calculated as follows, with *NCG* and *NCS* being the N concentrations (%) in grain and straw, respectively (see Table 2).:

$$Cupt_N = \left(\frac{GrainYield \times NCG}{100}\right) + \left(\frac{StrawYield \times NCS}{100}\right) \quad (eq. 4)$$

The use of maize harvest residues for fodder or soil fertility management is decided by each farm at harvest time (October 1st, see Figure 1). When a farm decides to adopt the practice of crop residue mulching, the basal maize yield increased by 10%, assuming a soil moisture conservation effect through mulching that has a positive effect on crop growth (we have also tested higher potential values, see section 3.4). In that case, crop residues are not available for free grazing, i.e. the fields are closed for cattle. The model does not consider uncontrolled entries by cattle on closed fields during the free grazing period. If a farm does not adopt mulching, a proportion of residues (specific to each farm type, Diarisso et al., 2015a) is harvested to build up a fodder stock, the remaining part of the residues being left on the fields and therefore accessible to any cattle. Straw stocks begin to be used when there is no longer a single field with enough food to feed the cattle.

2.3 Sensitivity analysis and simulated scenarios

First, we ran the AMBAWA model to test the model's sensitivity to a ±30% variation in values of three key model parameters (see Results 3.1). The following parameters or input variables were selected, since their values contain high uncertainty: 1) basal maize yield: ±30% of the default value of 400 kg ha^{-1}; 2) harvest index of maize: ±30% of the default value of 0.42; and 3) fraction of cattle faeces produced during the night: ±30% of the default value of 0.7. A local sensitivity analysis was implemented where all combinations of parameters (11 values for each parameter between defined bounds) were tested. The model was hereby run for five consecutive years with 10 replications given the stochastic nature of the model, for each set of parameter values and based on current agricultural practices without crop residue mulching.

Second, to analyze the evolution of maize yields through time for the scenario of the present conventional free-grazing systems, we ran the model for 10 years with the default values of the parameters (Table 2). Here, we focused on grain yield only, and could run 100 replications since computation time was strongly reduced with the sole focus on the grain yield output variable (see Results 3.2).

Third, we ran the model to assess the effect of the practice of crop residue mulching on maize productivity simulating the modified biomass (residues and manure) flows at farm and vilage scale. Scenarios with increased proportions of cropland under mulching were explored, i.e. from 10 to 90% of the croplands of the village, at increments of 10%. Given the contrasting crop yield responses to crop residue mulching reported in the literature, we hereby also assumed different scenarios of maize yield increase as a result of mulching, i.e. from 0 to 100% yield increase, at increments of 10%. For example, Gin et al. (2015) found through a meta-analysis yield increases with crop residue mulching from 5% to 97% depending on rainfall and fertilizer practices. Only the model results for the 10th cropping season were presented (see Results 3.3).

3 Results

3.1 Sensitivity analysis

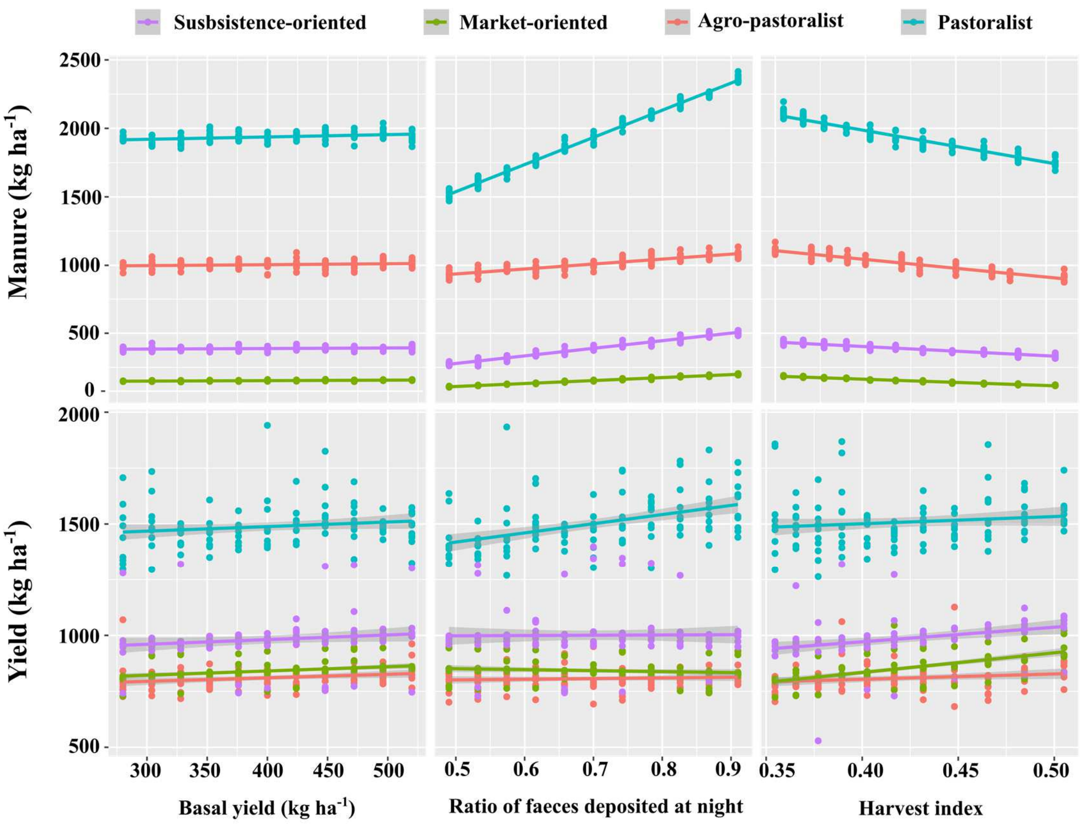

Figure 2: Impact of +/- 30% variation around default values of key parameters (basal grain yield, ratio of faeces deposited at night, harvest index) of the AMBAWA model on manure availability and maize grain yield for the four types of farms (subsistence-oriented farmers,

market-oriented farmers, agro-pastoralists, pastoralists). Points represent values from 10 replicated model runs and lines and shaded area represent respectively the linear least square regressions and their 95% confidence intervals. Values shown are those of the 5th season.

We analyzed the sensitivity of the model response to three model parameters that are key for simulating manure availability and crop productivity on the farms in the village, i.e. the basal maize grain yield, the harvest index of maize and the fraction of cattle faeces produced during the night. Basal yield is the least sensitive parameter of the three (Figure 2). A variation in basal yield from 280 to 520 kg ha^{-1} resulted in increases in simulated maize yield of 4.9, 6.6, 4.2 and 1.4%, corresponding to + 47, + 53, +34, and + 21 kg ha^{-1} respectively for SO, MO, AP and PA. The same trends were observed for the effects on manure availability, with minor increases of 3.0, 5.4, 3.0 and 0.3% (corresponding to +12, +8, +30 and +6 kg ha^{-1}) respectively for SO, MO, AP, and PA. In contrast, an increase in the value of the proportion of faeces deposited at night (from 0.49 to 0.91) led to different simulated patterns of manure availability and grain yield for the different farm types. In relative terms, the model response was highest for MO and SO, with an increase in simulated manure availability of 85% and 81% respectively, corresponding to +92 and +225 kg ha^{-1} of extra manure available on the farm, while model responses for AP and PA were only a 17% and 56% increase in manure availability, but corresponded to higher changes in absolute amounts of manure (+154 and +849 kg ha^{-1}). The resulting simulated grain yield responses with increased proportions of faeces produced at night by cattle were +0.77, -0.49, +2.6 and +11%, for respectively SO, MO, AP and PA. Lastly, the model response to an increase in the harvest index (from 0.35 to 0.50) was a reduction of manure availability for all farm types (from -17% for PA to -36% for MO), because of the decrease in the proportion of straw in the maize crop. However, the negative effect of reduced manure availability on grain yield was offset by the relative higher grain production over the total maize biomass, especially for MO and SO (+18% and +11% respectively).

3.2 Maize yield under free grazing of crop residues without mulching

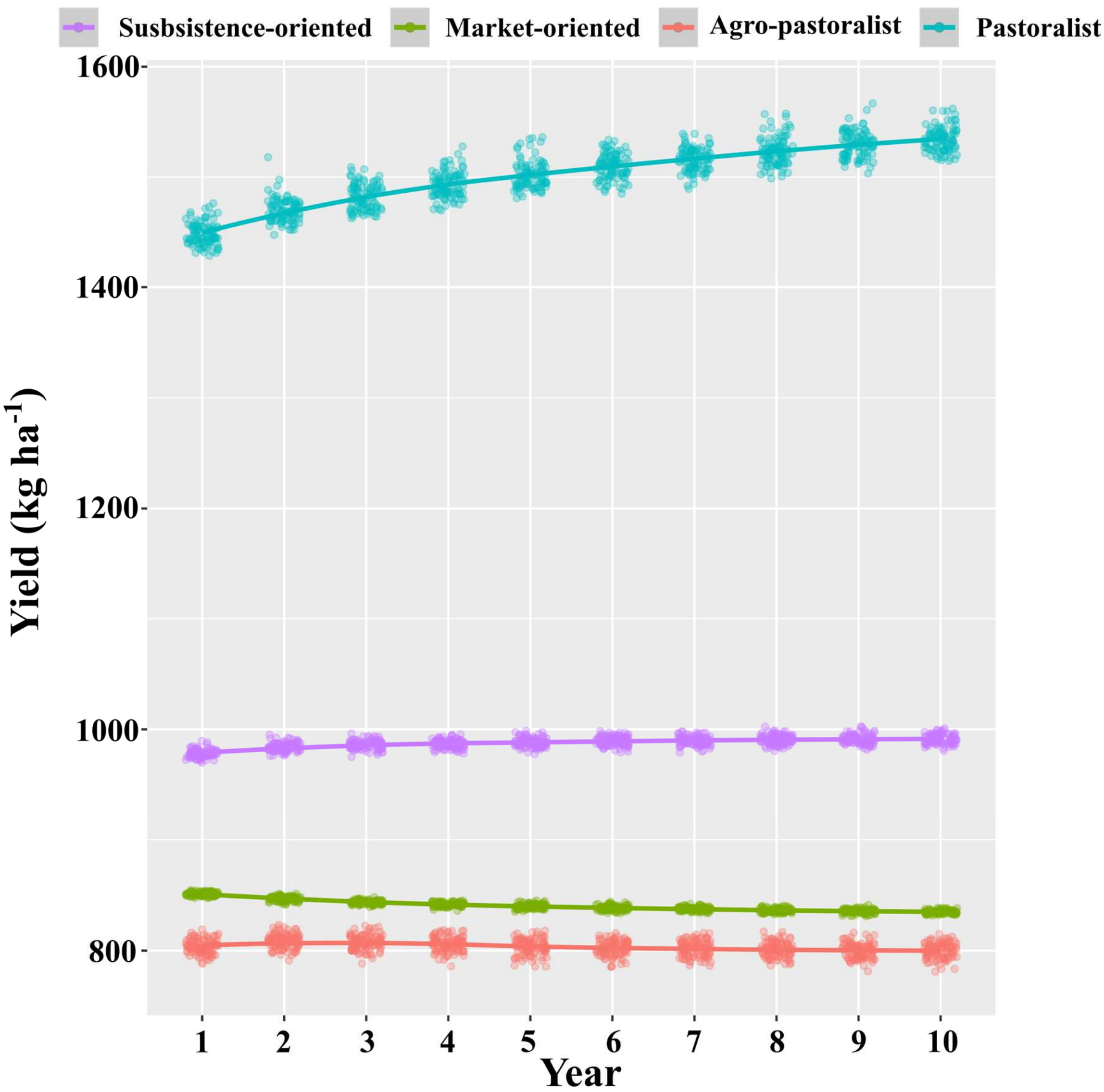

Figure 3: Evolution of simulated maize grain yield during 10 cropping seasons for the four farm types (subsistence-oriented farmers, market-oriented farmers, agro-pastoralists, pastoralists) under the scenario of the current conventional free-grazing systems (no crop

residue mulching) with the default values of the model parameters (see Table 2). Points represent values from 100 replicated model runs and lines represent the locally weighted regressions. Points are spread around the exact year value for graphical purpose.

Initial (season 1) maize grain yields as simulated by the model differed considerably between farm types, with the highest yield (1448 kg ha^{-1}) on PA farms and the lowest yields on AP and MO farms (804 and 844 kg ha^{-1}). These results can be explained by the amounts of organic and mineral fertilizers used by the different farm types at the start of season 1, which were pre-set values in the model simulations (Table 2). In the following seasons, yields are also affected by cattle and crop residue management and the resulting biomass (manure and residues) flows between farms and farm types. Simulated grain yields increased on PA farms with about +6% (+ 85 kg ha^{-1} after 10 years), whilst the yields on MO farms slightly decreased (-2%, - 16 kg ha^{-1}). On the two other farm types (SO and AP), grain yield remained stable. The steadily yield increase on PA farms can be explained by the increased manure availability as a result of net biomass flows into these farms. In contrast, MO farmers experience a net outflow of biomass (manure) due to the entrustment of their animals to pastoralists during the rainy season.

3.3 Village-level impact of crop residue mulching adoption

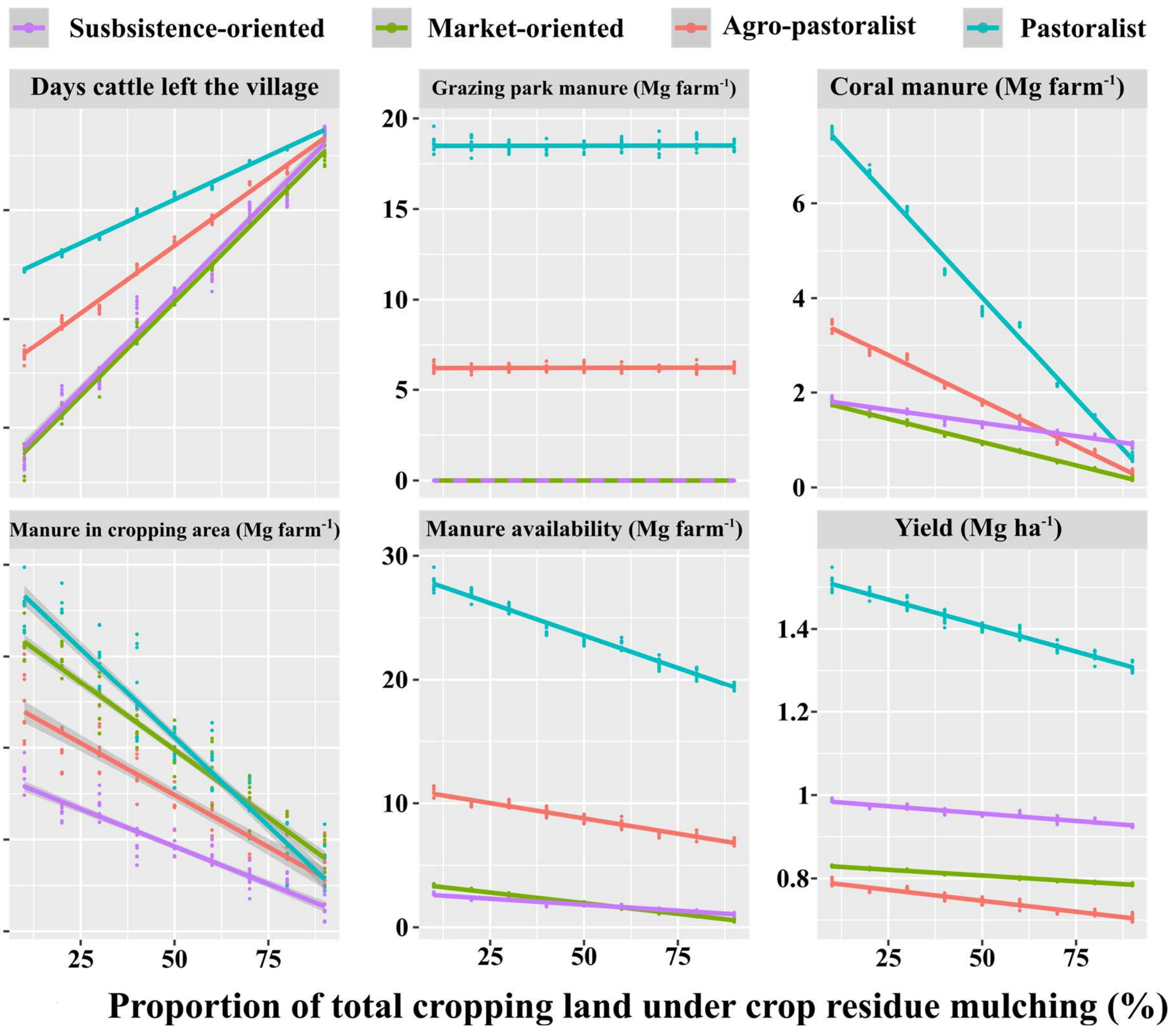

Figure 4: Impact of crop residue mulching (on 10 to 90% of total cropping land) on cattle migration, manure availability (manure in farm corals, in grazing parks, deposited in cropping area during free grazing, and the sum of these 3 sources) and maize grain yield for the four farm types (subsistence-oriented farmers, market-oriented farmers, agro-pastoralists, pastoralists). Days cattle left the village is expressed in number of days when livestock is outside the village because of fodder scarcity, yield is the average yield across all fields for a given farm type. Points represent values from 10 replicated model runs and lines and shaded

area represent respectively the linear least square regressions and their 95% confidence intervals. Values shown are those of the 10th cropping season.

Simulated maize grain yield (averaged across all fields per farm type) decreased with increasing proportion of cropping land under crop residue mulching for all farm types after 10 seasons, respectively -7.2, -5.8, -11.4 and -13.3% for SO, MO, AP and PA (Figure 4). The other plots in Figure 4 show the underlying factors that lead to the negative effects of crop residue mulching on yield at village scale, even though the model assumed that mulching had a direct positive effect of a 10% yield increase on hectare basis (see section 2.2). With 10% of the cropping area under mulching, cattle of SO, MO, AP and PA had to leave the village in transhumance for respectively 82, 86, 132, and 172 days, because of the reduced amount of crop residues during the dry season. Crop residues kept on the soil as mulch are not available as fodder. When 90% of the village is under mulching, cattle of SO, MO, AP and PA departed earlier during the dry season to spend respectively 236, 225, 232 and 236 days outside the village. This departure directly affected the manure deposited in the fields during free grazing (during the day), but also in the farm corals (during the night) (Figure 4). It should be noted that the manure available from grazing parks, produced during the rainy season, was not affected by the cattle movement outside the village. Consequently, when mulch is implemented on 90% instead of 10% of the cropping land, the total manure available for fertilization of the maize crop the next year was greatly reduced (-64, -84, -37 and –29%, respectively for SO, MO, AP and PA), and explains the impact on yields.

3.4 Impact of higher direct mulch effect on grain yield

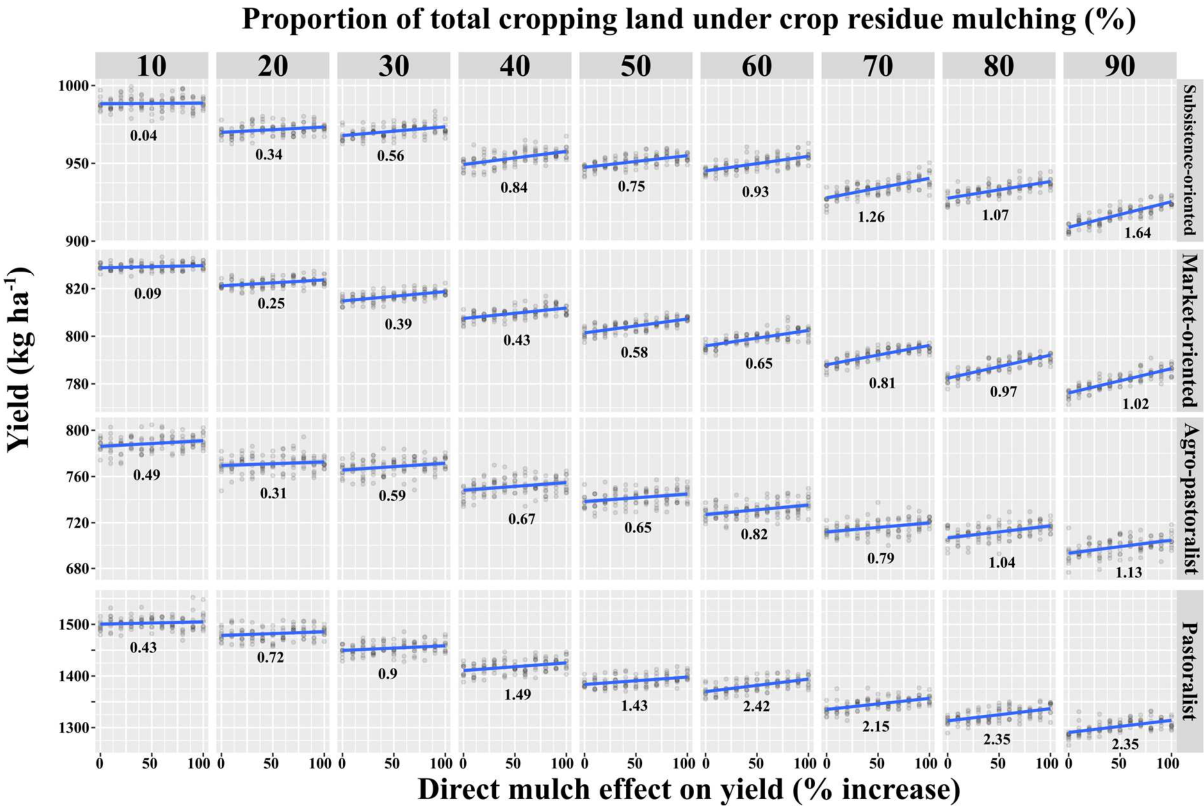

Figure 5: Impact of varying levels of direct crop residue mulching effects on grain yield (from zero to doubling yield) on simulated maize grain yield for the four farm types (subsistence-oriented farmers, market-oriented farmers, agro-pastoralists, pastoralists) and for different proportions of the total cropping land with the practice of crop residue mulching (10 to 90%). Yield per ha is the average yield across all fields for a given farm type. Points represent values from 10 replicated model runs and lines represent the linear least square regressions, with numbers (kg ha^{-1} per percent of additional yield with mulching) indicating the slope of the fitted regressions. Yield values shown are those of the 10th cropping season.

The direct yield effect of crop residue mulching on simulated grain yield at village scale (average yields across all fields for a given farm type, Figure 5) was almost null for SO and MO farmers (0.04 and 0.09 kg ha^{-1} per percent of additional yield due to mulching, respectively) and slightly positive for AP and PA farmers (0.49 and 0.43 kg ha^{-1} per percent of additional yield due to mulching, respectively) when 10% of land is under mulching. Under

90% of land under mulching, the direct effect of mulching was higher for SO and PA farmers (respectively 1.64 and 2.35 kg ha^{-1} per percent of additional yield due to mulching), compared to MO and AP farmers (1.02 and 1.13 kg ha^{-1} per percent of additional yield due to mulching, respectively). Figure 5 also shows that even when grain yields are doubled under crop residue mulching, this did not result in a doubling of grain production at village scale. This can be attributed to the negative effect of mulching on manure availability, as described before (section 3.3). Finally, Figure 5 shows that the total maize production at village level depended more on the percentage of cropping land under the practice of mulching than on a possible direct effect of mulching on yield *per se*, i.e. for a given farm type, changes of the positions of the regression lines from the left column to the right column were more important than the magnitude of their slopes within a cell.

4 Discussion

4.1 Biomass flows and crop productivity in agro-pastoral systems

The use of AMBAWA to analyze conservation agriculture introduction with crop residue mulching in the village of Koumbia in Burkina Faso helped better understanding and quantifying the possible impacts on manure production and maize productivity at farm and village scales, taking into account the diversity of farm structures and management practices.

The differentiated maize productivity among the four identified farming systems in the region (subsistence-oriented farmers, market-oriented farmers, agro-pastoralists and pastoralists) under the current free-grazing arrangement, with pastoralists having the highest yields due to largest manure availability, was shown through the model simulation (Figure 3). Subsistence-oriented farmers reached almost one ton grain yield per hectare owing to their manure availability, as their small cattle herd does not leave the village during the rainy season (grazing on the nearby fallow land). On the other hand, market-oriented farmers entrust their animals during the rainy season to pastoralists as they focus on crop production, but in doing so, they lose a significant share of their manure and therefore have low crop yields (Figure 3). Finally, agro-pastoralists, while owning both cattle and cropping land, have low yields due to the low use of mineral fertilizer, suggesting that crop-livestock interactions at farm level are not sufficient to sustain crop productivity in the region. These fertility and biomass flows patterns were already documented in the literature (e.g. Diarisso et al., 2015a), but through the AMBAWA model we were able to explain them and explore scenarios of alternative management. By doing so, we adopted the POM (Pattern-Oriented Modelling, Grimm et al., 2005) strategy, i.e first “decoding” observed patterns into a simple agent-based model, before using it to test *ex-ante* alternative scenarios that are unobserved yet.

Our study highlights that crop residue mulching with the assumption of a direct positive effect on crop yield due to soil moisture conservation (Ranaivoson et al., 2017) did not compensate for the yield decrease resulting from lesser amounts of manure available due to cattle migration outside the village during the dry season (Figure 5). This result clearly indicates that innovative management practices based on field plot testing should be evaluated in a broader context, e.g. taking into consideration their effects on livestock mobility and manure restitution. It is known that livestock is an important source of resilience in mixed crop-livestock farming systems (Turner et al. 2014). Keeping livestock within the village has a key role for livelihoods, particularly when soils are depleted and mineral fertilizer inputs are beyond reach of the farmers. Thus, our study demonstrates the need to consider the multifunctionality of livestock in smallholder systems in sub-Saharan Africa (Salmon et al, 2019). As expected, the introduction of conservation agriculture with the practice of crop residue mulching affected livestock owners more than crop producers (-13.3% yield reduction for pastoralists versus -5.8% for market-oriented crop farmers, when the proportion of land under crop residue mulching increases from 10 to 90%). Our results also highlight the importance of considering the diversity of farmers' needs and characteristics when proposing a new technology such as conservation agriculture. This reinforces the need for the identification of socio-ecological niches where conservation agriculture can be implemented with success, rather than promoting its broad-scale dissemination (Giller et al., 2009).

In this study, the model was used to assess the effects of crop residue mulching on crop productivity and its sustainability, but the model could potentially be used to explore the effects of other modes of management of crop residues such as compost production or the introduction of fodder crops grown in rotation or in association with maize. Fodder crops can favor synergies between feeding livestock and maintaining soil fertility through biomass and/or nitrogen additions when they are legume species (e.g. Andriarimalala et al., 2013). Further research with AMBAWA may help to identify improved biomass management with a portfolio of practices instead of solely crop residue management as it was done in this first application of AMBAWA.

4.2 Limits and potential improvements of the AMBAWA model

With AMBAWA, we followed the parsimony principle, which says that 'models should be as simple as possible but as complex as necessary for the specific modelling objective, and not be overloaded with unnecessary details, and have minimum data requirements' (Adam et al. 2012). The development of the AMBAWA model followed a classic approach where layers of complexity are built step by step from a simple conceptual model. In our study, a computer scientist worked closely with agronomists by iterating feedback loops of model conceptualization-implementation-coding-testing (Le Page, 2017). Despite being based on empirical data gathered in the village of Koumbia (Diarisso et al. 2015a, Diarisso et al. 2015b), the model does not represent the spatial peculiarities of the study area. In its current form, AMBAWA is not a pure abstract theoretical model (KISS; Keep It Simple and Stupid), nor a realistic empirical model describing all processes at stake (KIDS; Keep It Descriptive and Stupid), but it is located in an 'in between" zone as identified by Sun et al. (2016), i.e the KILT approach (Keep It a Learning Tool, Le Page and Perrotton, 2017) (Figure 6). The KILT approach offers an alternative to the dichotomist vision of theoretical versus empirical models. The stylized KILT-type models focus on the co-construction of alternatives with stakeholders, and therefore should not be too complicated, nor too simplistic as they need to be able to offer realistic simulations to co-build alternative farming systems. In its current form, AMBAWA falls exactly into this category of model.

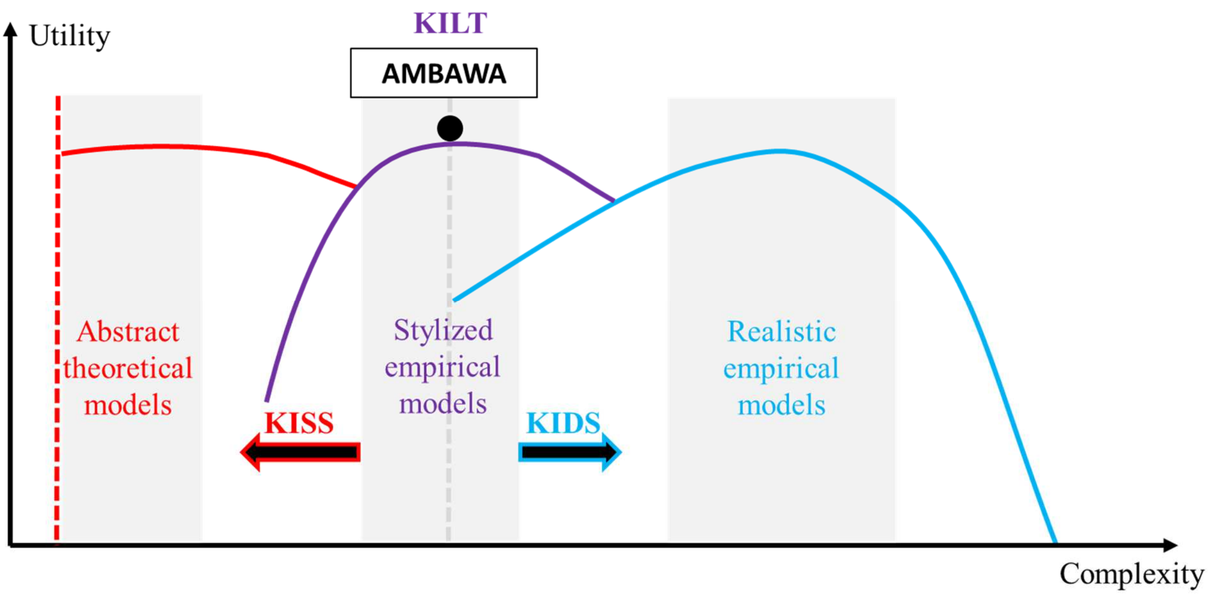

Figure 6: The position of the AMBAWA model within the diagram of 'utility' of simulation models as a function of 'complexity'. Red, purple and blue lines represent the utility function of the abstract, stylized and realistic models, respectively. Arrows represent the driving forces of both KISS and KIDS approaches (Le Page and Perrotton, 2017, adapted from Sun al al., 2016).

KISS; Keep It Simple and Stupid; KIDS; Keep It Descriptive and Stupid and KILT: Keep It a Learning Tool.

Even though the AMBAWA model was on purpose designed with a low level of complexity (Figure 6), we can identify various refinements for its further use in assessing innovative management practices.

With the current model, once crop residue sources are depleted, the cattle instantaneously leave the village to search for other sources of feed. In reality, in the study region alternative feed sources are used when biomass scarcity occurs in the middle of the dry season. One of them, which could be included in the model, is the use of cottonseed cake, a well-known by-product of cotton production. Even if cottonseed cake is costly, it can constitute a significant share of the feed ratio of cattle, of up to 130 kg TLU^{-1} yr^{-1}(Vall et al., 2006). Additionally, an improved version of the model could incorporate more complex processes such as variable cattle feed intake rates throughout the year, with for example low daily fodder needs during stress periods (Assouma et al., 2018), and more accurate zootechnical data such as the ratio of faeces produced at night which appeared as a sensitive parameter in the model (Figure 2). Lastly, an important aspect on the livestock system to be considered concerns the manure quality, as all manure in the AMBAWA model is considered to have the same quality, i.e. the same fertilization potential. It has been observed that quality of manure in mixed crop-livestock smallholder systems in sub-Saharan Africa can vary greatly (Rufino et al., 2007). For example, the manure deposited in the parks, mixed with surface soil through cattle trampling ("poudrette"), loses a large amount of its nitrogen content in comparison with the manure directly deposited on the fields during crop residue free grazing (Ganry and Badiane, 1998). Hence, nitrogen inputs from manure produced in parks may have been overestimated in AMBAWA.

The cropping system is also deliberately simplified in AMBAWA but further development of the model could include more accurate empirical-based rules and equations. For example, the cropping calendar is fixed in the current version of the model while different farmers adopt different practices and different sowing or harvesting dates, in particular to cope with whether variability or with pests and diseases (Madege et al., 2018). At village scale, this diversity of cropping calendars will potentially entail different biomass flow patterns and possibly new synergies between farmers (e.g. an early crop in a relay-intercropping system could generate fodder during the rainy season). Finally, simulation of soil fertility can certainly be improved in the model, e.g. through simulating soil organic matter dynamics and its impact on crop yields. Ultimately, such improvement could be implemented by coupling AMBAWA to an existing process-based crop model (e.g. DSSAT, Jones et al. 2003; STICS, Brisson et al., 2003; APSIM, Keating et al., 2003). Amongst others, this coupling would require daily data on temperature and rainfall, instead of a simple description of the season in two periods. However, we would like to emphasize here that the complexity included in simulation models should go with the specific research question addressed (Passioura, 1996).

4.3 Perspectives for the use of the AMBAWA model

Although refinements of AMBAWA could be envisaged (see section 4.2), the model in its current state permits to simulate the differentiation of crop productivity among farming systems under the current free-grazing rules in an agro-pastoral area. Highest yields were simulated for livestock owners due to transfer of manure to their fields. Such transfers of fertility that results from cattle ownership and management have been described previously (Manlay et al., 2004; Diariosso et al., 2015a, 2015b; Vall et al., 2006), but were never explored through simulation modelling. Compared to current whole-farm models, such as Cikeda (Sempore et al., 2015) or FarmSim (van Wijk et al., 2009) that were used for the analysis of the impact of innovative agricultural practices on crop productivity at farm level, AMBAWA also considers the effect of innovative practices, including the interactions between farmers, on the restitution of manure by animals. Compared to an existing model that explores impact of agricultural land use in West Burkina Faso at field and farm scales (Jahel et al., 2017), AMBAWA also simulates livestock systems and their mobility, a key component of farming system resilience in the agro-pastoral areas of Burkina Faso.

Consequently, AMBAWA contributes to existing agent-based models that assess the complexity of agricultural systems (e.g. Schreinemachers and Berger, 2011; Belem et al., 2011; Rasch et al., 2017, Grillot et al., 2018a, 2018b) but with a specific emphasis on the management of crop residues that are a key resource in the smallholder systems of West Africa. It has been emphasized that there is an urgent need to improve soil fertility (Stewart et al., 2020) without exposing conflicts between crop farmers and pastoralists (Andrieu et al., 2015) through defining collectively rules and land charters for crop residue collection (Dabire et al., 2017). AMBAWA can consequently be a useful discussion tool for stakeholders (farmers, traditional and administrative authorities) involved in the management of crop residues at the village level in order to co-design differentiated scenarios for sustainable use of collective resources.

Finally, AMBAWA has already been presented in various scientific events (Berre et al., 2019), in new research projects where it will be used (DSCATT, https://dscatt.net/; 3F, https://www.ccrp.org/grants/3f/), and raised exciting discussions on soil fertility management and crop-livestock integration using interactive model simulations. In a close future, the model will be adapted to interact with farmers and enrich the socio-economic component of the model, for instance as a ‘serious game’ (Michalscheck et al., 2020) on biomass flows at village scale. For example, serious board games (in which farmers decide to growth certain crops and allocate livestock to grazing areas according to external information such as climate or market prices) will allow generating co-learning cycles through which farmers learn about the impact of their decisions on soil fertility patterns at farm and village scale, and through which researchers will better understand drivers of farmers’ decisional processes.

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6 Conclusions

In order to assess the effects of crop residue management (mulching versus cattle feeding) on crop productivity in a village of central Burkina Faso, we developed and used an agent-based model (AMBAWA) that simulates the complex flows of biomass and nutrients between crop and livestock systems of farms at village scale. We showed that the introduction of crop residue mulching as part of the practice of conservation agriculture had contrasting effects among the type of farmers. With mulching, the amount of available maize residues for cattle feeding during the dry season decreased, so did the amount of animal manure available for soil amendment as cattle had to leave the village to search for feed elsewhere. As a result, the assumed direct positive effect of mulching on crop productivity did not compensate the yield losses due to lesser amounts of manure available at village scale, especially for cattle owners (pastoralists and agro-pastoralists). This first version of AMBAWA was on purpose designed with a low level of complexity. Refinements to the model can be implemented for its further use in assessing other innovative management practices and arrangements between farmers for their impact on the agricultural systems at field, farm and village scale.

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