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1 **Biomass flows in an agro-pastoral village in West-Africa: who benefits from** 2 **crop residue mulching?**

3
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18 **Abstract**

19 In West Africa, new management practices such as conservation agriculture with crop residue
20 mulching can improve crop yields for individual farmers. However, in a context of complex
21 social interactions between farmers, the introduction of such practices can also lead to
22 conflicts between private interests and communal use of resources, for example the free-
23 grazing of crop residues. The objective of this paper was to assess ex-ante the impacts of the
24 practice of crop residue mulching on crop productivity in a village of central Burkina Faso
25 using an agent-based model (AMBAWA) that simulates the flows of biomass and nutrients
26 between crop and livestock systems at the village scale. The model considers the interactions
27 between four types of farmers that were identified in the study site: subsistence-oriented crop
28 farmers, market-oriented crop farmers, agro-pastoralists and pastoralists. The model simulated

29 increased cattle migration outside the village due to increased crop residue scarcity during the
30 dry season with increased proportions of cropland under the practice of conservation
31 agriculture, decreasing the manure availability at village scale. Consequently, the assumed
32 direct yield increases as a result of mulching due to soil moisture conservation did not
33 compensate for the yield losses resulting from lesser amounts of manure available. This effect
34 was felt most strongly by farmers who own relatively large numbers of cattle (agro-
35 pastoralists and pastoralists). The total maize production at village level depended more on
36 the proportion of cropping land that was available for grazing by cattle, and thus not mulched,
37 than on a possible direct effect of mulching on yield per se. The AMBAWA model can
38 support discussion among stakeholders (farmers, traditional and administrative authorities)
39 who are involved in the private and communal management of crop residues and other
40 biomass resources, in order to co-design effective arrangements and practices for their
41 sustainable use.

42

43 **Keywords:**

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

46

47 **1 Introduction**

48 In the agro-pastoral regions of West Africa, crop residues and livestock play an important role
49 in soil fertility management, especially in the context of a growing disappearance of land
50 fallow practices (Bationo et al., 2007; Manlay et al., 2004). Traditional by-laws regulating the
51 communal use of natural resources prescribe the grazing of crop residues by free-roaming
52 village or transhumant livestock during the dry season. To respond to the increased food
53 demand in the rural and urban areas, new crop management practices based on recycling of

54 crop residues as compost or their use as mulch in fields are promoted by international and
55 national research and development programs (Nafi et al., 2020). These practices can
56 potentially improve crop yields for individual farmers but can also lead to conflicts between
57 private interests (i.e. soil fertility maintenance of fields by individual farmers) and communal
58 agreements (i.e. feeding the village herd during the dry season) (Andrieu et al., 2015).

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

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

76 In the context of Africa, agent-based models have been particularly applied to analyze the
77 interactions between human dynamics (immigration, emigration, and population growth) and
78 the environment (e.g. soil quality) (Bah et al., 2006; Belem et al., 2011; Grinblat et al., 2015),

79 and to study the adaptations of farmers to climate change (Wossen and Berger, 2015; Amadou
80 et al., 2018; Belem et al., 2018). Besides, this type of models has also been used to quantify
81 the impact of agricultural expansion on livestock production and nutrient cycling (Grillot et
82 al, 2018), and to assess the effect of policy interventions on the adoption of conservation
83 agriculture (Bell et al., 2016) or on the socio-ecological resilience of communal rangeland
84 systems (Rasch et al., 2017). In some of these studies, both the cropping and livestock
85 systems were considered, the livestock system often being seen as a source of capital and
86 social resilience. However, so far, no studies in sub-Saharan Africa have explored the effects
87 of the introduction of a new agricultural technology on organic resource exchanges between
88 farmers, and their consequences for crop productivity.

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

102

103 2 **Materials and methods**

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

111 **2.1 Study area and farming systems**

112 2.1.1 Study area

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

127 most agricultural production systems are mixed crop-livestock farms that employ animal
128 traction and use manure for soil fertility management.

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130 2.1.2 Typology of farming systems and farm resource flows

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

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154 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

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

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158 The subsistence-oriented farms are characterized by low resource endowments; maize grain
 159 production is exclusively used for own consumption. They have a small herd and small
 160 ruminants represent a relatively high proportion (25%) of the total tropical livestock units
 161 (TLU) on the farm. Off-farm activities (masonry and trading activities) are a relatively
 162 important activity for this farm type, representing on average 15% of the total household
 163 activities. The market-oriented farms have medium resource endowments. Cotton is the main
 164 crop, grown under contract farming with the semi-private SOFITEX (Société Burkinabè des
 165 Fibres Textiles) company. These farms sell also part of their maize production on local
 166 markets. Agro-pastoralists were previously market-oriented farmers who built up a relatively

167 large herd of cattle with the income generated from cotton production. The fourth type of
168 farmers represent Fulani pastoralists. In the past these farmers were nomadic, but they became
169 sedentary in recent decades and began growing crops. Livestock production is clearly the
170 main activity for this group of farmers.

171

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

178 **2.2 Presentation of the AMBAWA model**

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

186 The basic idea underlying the model is to explore the effects of resource flows (organic and
187 mineral fertilizers, crop residues, manure) between farms, crop and livestock systems and
188 crop fields on crop productivity in the agro-pastoral areas of West Africa. We considered the
189 village of Koumbia as a situation to inspire the creation of a stylized model, capturing the
190 main features of the agro-ecosystem rather than providing a realistic representation.
191 Consequently, significant simplifications guided the design of the model. For instance, it

192 includes only the maize crop since it is the most cropped cereal in the study area and its
193 residues are the major source of fodder for livestock (Andrieu et al., 2015). The overall
194 purpose of the model is to compare the effects of different scenarios of crop residue
195 management (mulching versus cattle feeding) on crop productivity at the field, farm, and
196 village scales. To consider our model realistic enough for its purpose, we use quantitative
197 patterns of manure and crop yield changes over time, as well as the date on which animals
198 leave the territory due to a lack of fodder.

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

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Entity	State variable / parameter	Farm type	Value	Unit	Source
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		SO	4		
	Farm size	MO	10	ha farm ⁻¹	Diarisso et al. 2015a
		AP	8		
		PA	7		
		SO	31		
	Harvest of maize stalks	MO	29	% of total production	Diarisso et al. 2015a
		AP	54		
		PA	46		
Farm		SO	2-5		
	Cattle herd size (min-max)	MO	4-8	TLU farm ⁻¹	Diarisso et al. 2015a
		AP	12-20		
		PA	50-60		
		SO	3		
	Use of organic N fertilizer (first season, then simulated by the model)	MO	12	kg N ha ⁻¹	Diarisso et al. 2015a
		AP	13		
		PA	39		
		SO	51		
	Use of mineral N fertilizer (all seasons)	MO	45	kg N ha ⁻¹	Diarisso et al. 2015a
		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	
	Manure deposited (initial value)		0	kg farm ⁻¹	
Agricultural field	N balance (initial value)		0	kg farm ⁻¹	
	Fertility (initial value)		1		
	Straw residue level (initial value)		0	kg farm ⁻¹	
	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
Maize	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	
			4.5	kg of dry matter TLU ⁻¹ day ⁻¹	Assouma et al., 2018
	Minimal fodder consumption rate				
			6.25	kg of dry matter TLU ⁻¹ day ⁻¹	Defoer et al., 1998
Cattle	Maximal fodder consumption rate				
	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	-	

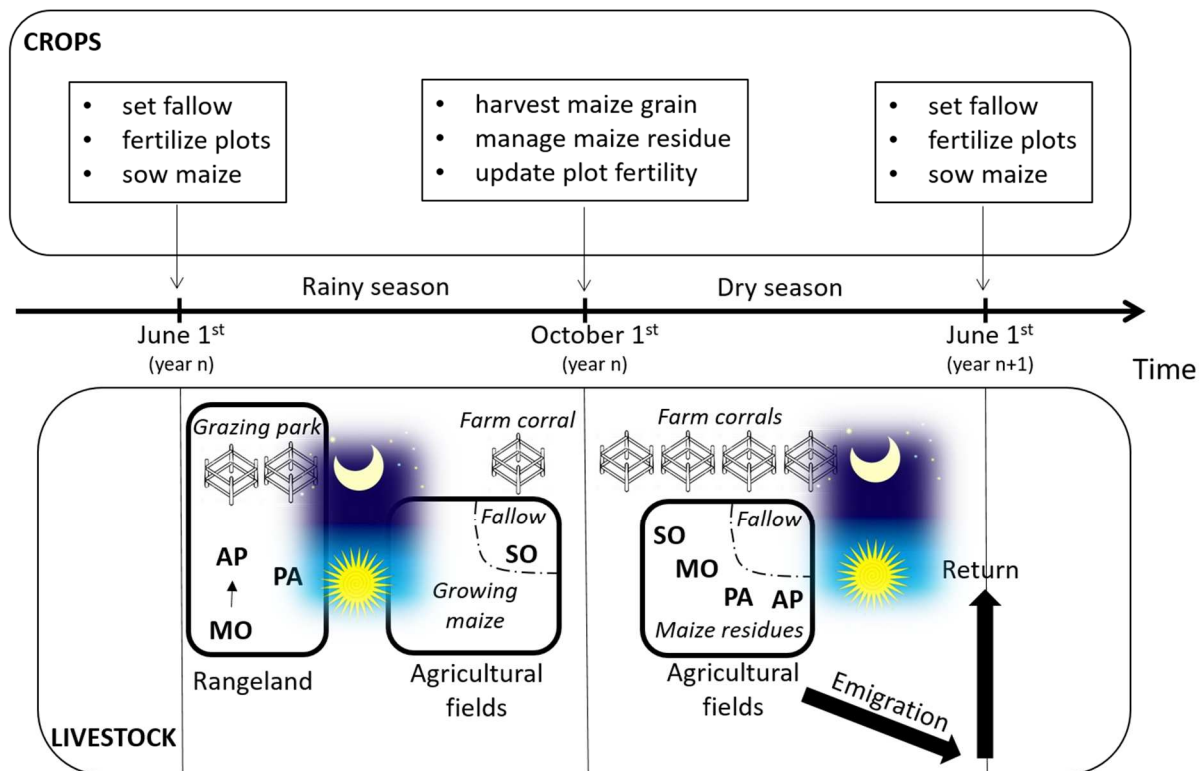
221 SO: subsistence-oriented crop farmers; MO: market-oriented crop farmers; AP: agro-pastoralists; PA:

222 pastoralists; N: nitrogen; TLU: tropical livestock unit

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

229



230

231

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

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

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

237 The location of cattle feeding and production of faeces is processed every half-day according
 238 to seasonal patterns specific to each farm type (see Figure 1). During the day, animals feed

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

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

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

263 $GrainYield = (BasalYield \times FertIndex) + ((Min_N + Org_N) \times NAE)$ (eq. 1)

264 $StrawYield = GrainYield \times \left(\frac{1 - HI}{HI}\right)$ (eq. 2)

265

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

271 $FertIndex^{t+1} = FertIndex^t + \left(\frac{Min_N + Org_N}{Cupt_N}\right)$ (eq. 3)

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

275 $Cupt_N = \left(\frac{GrainYield \times NCG}{100}\right) + \left(\frac{StrawYield \times NCS}{100}\right)$ (eq. 4)

276

277 The use of maize harvest residues for fodder or soil fertility management is decided by each
 278 farm at harvest time (October 1st, see Figure 1). When a farm decides to adopt the practice of
 279 crop residue mulching, the basal maize yield increased by 10%, assuming a soil moisture
 280 conservation effect through mulching that has a positive effect on crop growth (we have also
 281 tested higher potential values, see section 3.4). In that case, crop residues are not available for
 282 free grazing, i.e. the fields are closed for cattle. The model does not consider uncontrolled
 283 entries by cattle on closed fields during the free grazing period. If a farm does not adopt
 284 mulching, a proportion of residues (specific to each farm type, Diarisso et al., 2015a) is

285 harvested to build up a fodder stock, the remaining part of the residues being left on the fields
286 and therefore accessible to any cattle. Straw stocks begin to be used when there is no longer a
287 single field with enough food to feed the cattle.

288

289 **2.3 Sensitivity analysis and simulated scenarios**

290 First, we ran the AMBAWA model to test the model's sensitivity to a $\pm 30\%$ variation in
291 values of three key model parameters (see Results 3.1). The following parameters or input
292 variables were selected, since their values contain high uncertainty: 1) basal maize yield:
293 $\pm 30\%$ of the default value of 400 kg ha^{-1} ; 2) harvest index of maize: $\pm 30\%$ of the default
294 value of 0.42; and 3) fraction of cattle faeces produced during the night: $\pm 30\%$ of the default
295 value of 0.7. A local sensitivity analysis was implemented where all combinations of
296 parameters (11 values for each parameter between defined bounds) were tested. The model
297 was hereby run for five consecutive years with 10 replications given the stochastic nature of
298 the model, for each set of parameter values and based on current agricultural practices without
299 crop residue mulching.

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

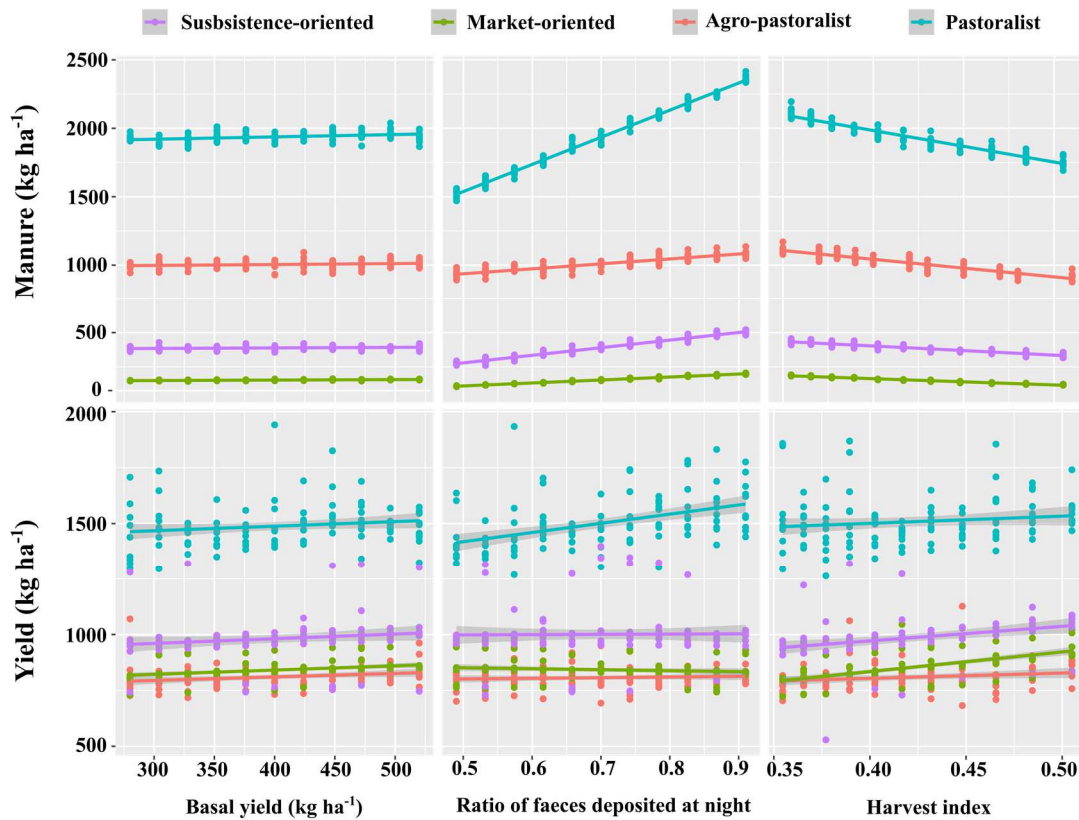
305 Third, we ran the model to assess the effect of the practice of crop residue mulching on maize
306 productivity simulating the modified biomass (residues and manure) flows at farm and vilage
307 scale. Scenarios with increased proportions of cropland under mulching were explored, i.e.
308 from 10 to 90% of the croplands of the village, at increments of 10%. Given the contrasting

309 crop yield responses to crop residue mulching reported in the literature, we hereby also
 310 assumed different scenarios of maize yield increase as a result of mulching, i.e. from 0 to
 311 100% yield increase, at increments of 10%. For example, Gin et al. (2015) found through a
 312 meta-analysis yield increases with crop residue mulching from 5% to 97% depending on
 313 rainfall and fertilizer practices. Only the model results for the 10th cropping season were
 314 presented (see Results 3.3).

315

316 3 Results

317 3.1 Sensitivity analysis



318

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

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

325

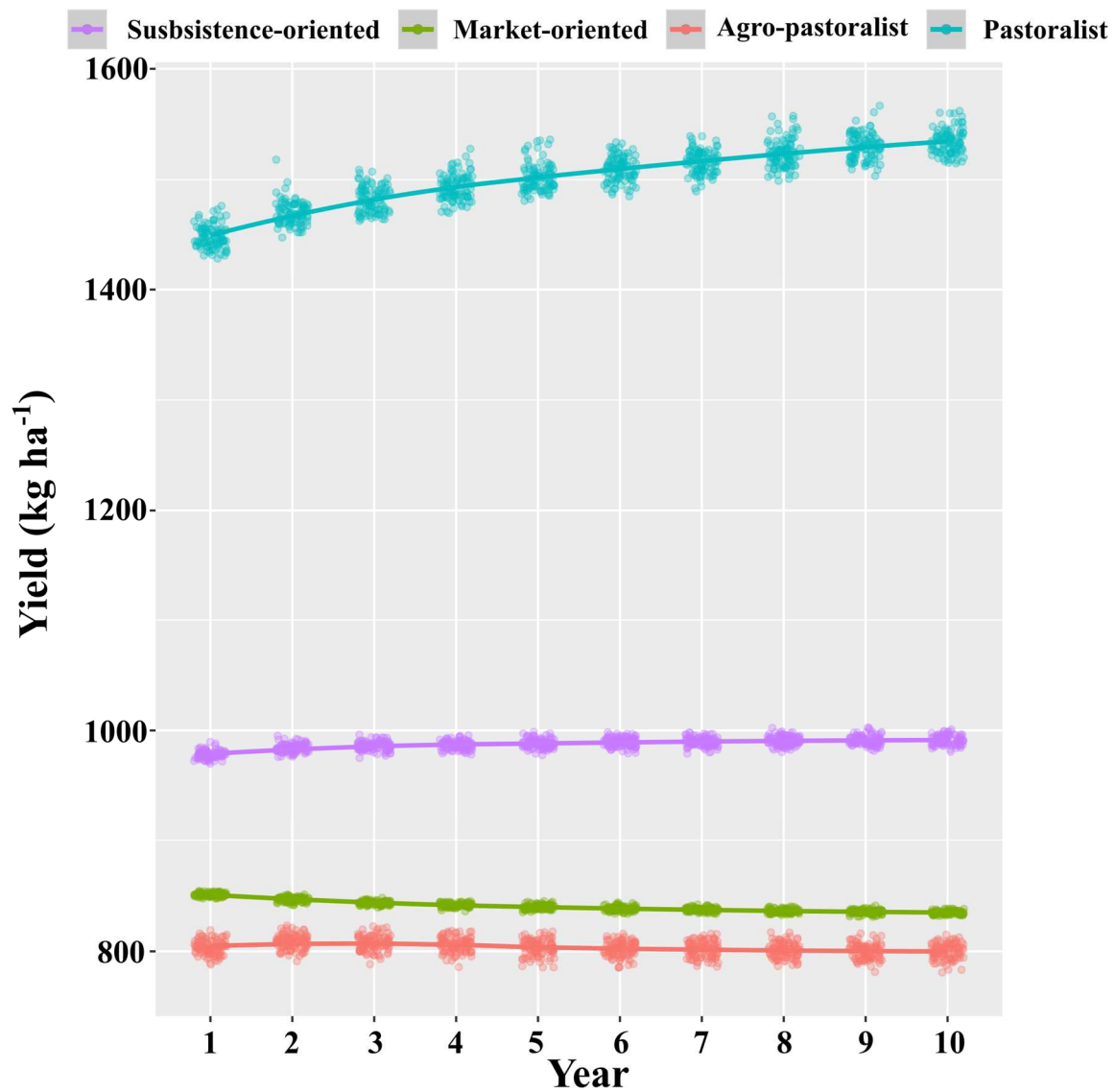
326 We analyzed the sensitivity of the model response to three model parameters that are key for
327 simulating manure availability and crop productivity on the farms in the village, i.e. the basal
328 maize grain yield, the harvest index of maize and the fraction of cattle faeces produced during
329 the night. Basal yield is the least sensitive parameter of the three (Figure 2). A variation in
330 basal yield from 280 to 520 kg ha⁻¹ resulted in increases in simulated maize yield of 4.9, 6.6,
331 4.2 and 1.4%, corresponding to + 47, + 53, +34, and + 21 kg ha⁻¹ respectively for SO, MO,
332 AP and PA. The same trends were observed for the effects on manure availability, with minor
333 increases of 3.0, 5.4, 3.0 and 0.3% (corresponding to +12, +8, +30 and +6 kg ha⁻¹)
334 respectively for SO, MO, AP, and PA. In contrast, an increase in the value of the proportion
335 of faeces deposited at night (from 0.49 to 0.91) led to different simulated patterns of manure
336 availability and grain yield for the different farm types. In relative terms, the model response
337 was highest for MO and SO, with an increase in simulated manure availability of 85% and
338 81% respectively, corresponding to +92 and +225 kg ha⁻¹ of extra manure available on the
339 farm, while model responses for AP and PA were only a 17% and 56% increase in manure
340 availability, but corresponded to higher changes in absolute amounts of manure (+154 and
341 +849 kg ha⁻¹). The resulting simulated grain yield responses with increased proportions of
342 faeces produced at night by cattle were +0.77, -0.49, +2.6 and +11%, for respectively SO,
343 MO, AP and PA. Lastly, the model response to an increase in the harvest index (from 0.35 to
344 0.50) was a reduction of manure availability for all farm types (from -17% for PA to -36% for
345 MO), because of the decrease in the proportion of straw in the maize crop. However, the
346 negative effect of reduced manure availability on grain yield was offset by the relative higher

347 grain production over the total maize biomass, especially for MO and SO (+18% and +11%
348 respectively).

349

350 3.2 Maize yield under free grazing of crop residues without mulching

351



352

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

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

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

372

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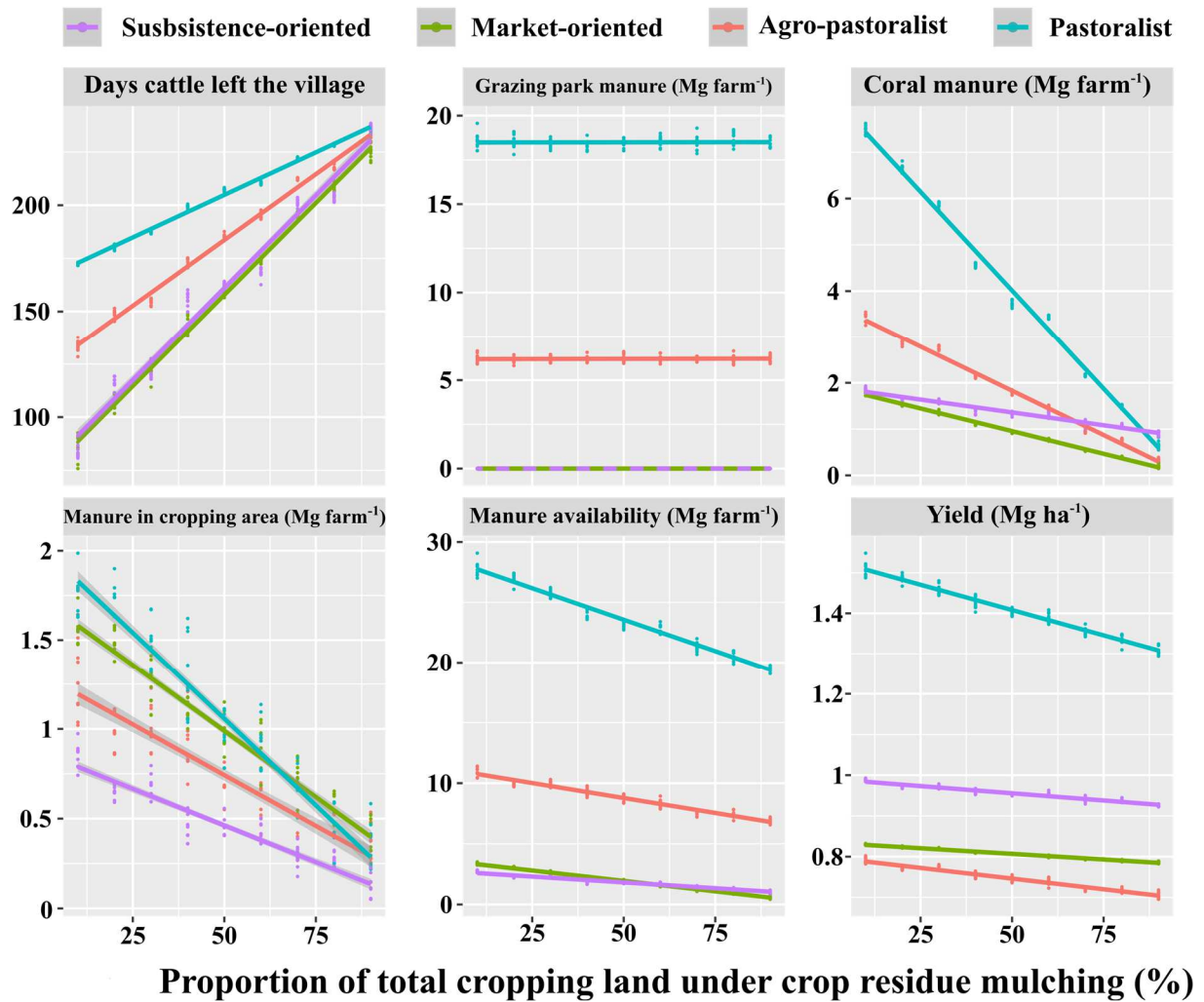
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379 **3.3 Village-level impact of crop residue mulching adoption**



380

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

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

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

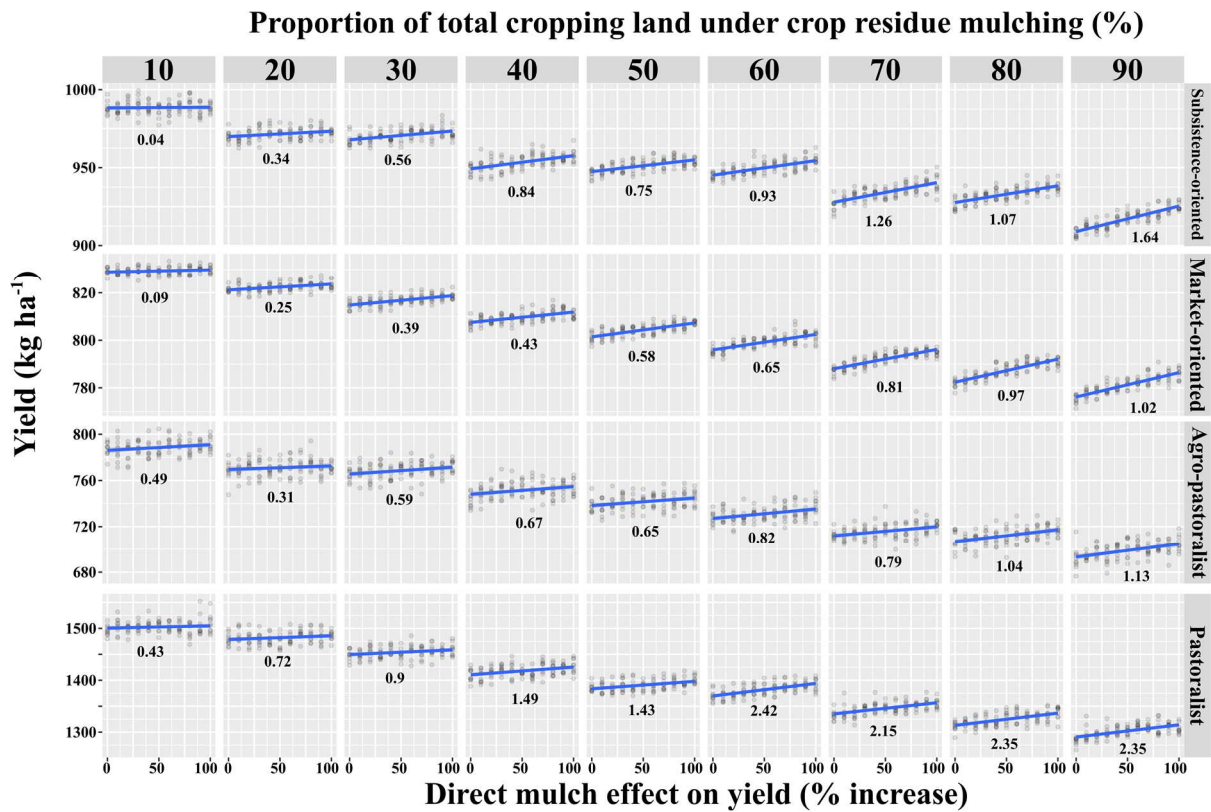
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412 **3.4 Impact of higher direct mulch effect on grain yield**



413
 414 **Figure 5:** Impact of varying levels of direct crop residue mulching effects on grain yield
 415 (from zero to doubling yield) on simulated maize grain yield for the four farm types
 416 (subsistence-oriented farmers, market-oriented farmers, agro-pastoralists, pastoralists) and for
 417 different proportions of the total cropping land with the practice of crop residue mulching (10
 418 to 90%). Yield per ha is the average yield across all fields for a given farm type. Points
 419 represent values from 10 replicated model runs and lines represent the linear least square
 420 regressions, with numbers (kg ha^{-1} per percent of additional yield with mulching) indicating
 421 the slope of the fitted regressions. Yield values shown are those of the 10th cropping season.

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

427 90% of land under mulching, the direct effect of mulching was higher for SO and PA farmers
428 (respectively 1.64 and 2.35 kg ha⁻¹ per percent of additional yield due to mulching), compared
429 to MO and AP farmers (1.02 and 1.13 kg ha⁻¹ per percent of additional yield due to mulching,
430 respectively). Figure 5 also shows that even when grain yields are doubled under crop residue
431 mulching, this did not result in a doubling of grain production at village scale. This can be
432 attributed to the negative effect of mulching on manure availability, as described before
433 (section 3.3). Finally, Figure 5 shows that the total maize production at village level depended
434 more on the percentage of cropping land under the practice of mulching than on a possible
435 direct effect of mulching on yield *per se*, i.e. for a given farm type, changes of the positions of
436 the regression lines from the left column to the right column were more important than the
437 magnitude of their slopes within a cell.

438

439 **4 Discussion**

440 **4.1 Biomass flows and crop productivity in agro-pastoral systems**

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

445 The differentiated maize productivity among the four identified farming systems in the region
446 (subsistence-oriented farmers, market-oriented farmers, agro-pastoralists and pastoralists)
447 under the current free-grazing arrangement, with pastoralists having the highest yields due to
448 largest manure availability, was shown through the model simulation (Figure 3). Subsistence-
449 oriented farmers reached almost one ton grain yield per hectare owing to their manure
450 availability, as their small cattle herd does not leave the village during the rainy season

451 (grazing on the nearby fallow land). On the other hand, market-oriented farmers entrust their
452 animals during the rainy season to pastoralists as they focus on crop production, but in doing
453 so, they lose a significant share of their manure and therefore have low crop yields (Figure 3).
454 Finally, agro-pastoralists, while owning both cattle and cropping land, have low yields due to
455 the low use of mineral fertilizer, suggesting that crop-livestock interactions at farm level are
456 not sufficient to sustain crop productivity in the region. These fertility and biomass flows
457 patterns were already documented in the literature (e.g. Diarisso et al., 2015a), but through the
458 AMBAWA model we were able to explain them and explore scenarios of alternative
459 management. By doing so, we adopted the POM (Pattern-Oriented Modelling, Grimm et al.,
460 2005) strategy, i.e first “decoding” observed patterns into a simple agent-based model, before
461 using it to test *ex-ante* alternative scenarios that are unobserved yet.

462 Our study highlights that crop residue mulching with the assumption of a direct positive effect
463 on crop yield due to soil moisture conservation (Ranaivoson et al., 2017) did not compensate
464 for the yield decrease resulting from lesser amounts of manure available due to cattle
465 migration outside the village during the dry season (Figure 5). This result clearly indicates
466 that innovative management practices based on field plot testing should be evaluated in a
467 broader context, e.g. taking into consideration their effects on livestock mobility and manure
468 restitution. It is known that livestock is an important source of resilience in mixed crop-
469 livestock farming systems (Turner et al. 2014). Keeping livestock within the village has a key
470 role for livelihoods, particularly when soils are depleted and mineral fertilizer inputs are
471 beyond reach of the farmers. Thus, our study demonstrates the need to consider the
472 multifunctionality of livestock in smallholder systems in sub-Saharan Africa (Salmon et al,
473 2019). As expected, the introduction of conservation agriculture with the practice of crop
474 residue mulching affected livestock owners more than crop producers (-13.3% yield reduction
475 for pastoralists versus -5.8% for market-oriented crop farmers, when the proportion of land

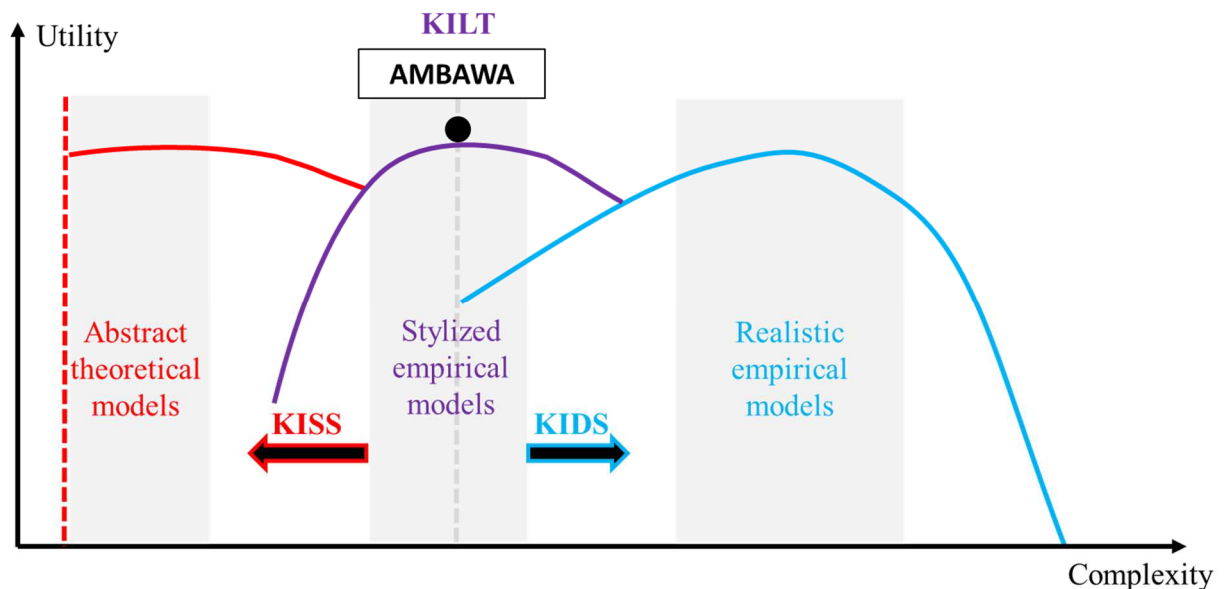
476 under crop residue mulching increases from 10 to 90%). Our results also highlight the
477 importance of considering the diversity of farmers' needs and characteristics when proposing
478 a new technology such as conservation agriculture. This reinforces the need for the
479 identification of socio-ecological niches where conservation agriculture can be implemented
480 with success, rather than promoting its broad-scale dissemination (Giller et al., 2009).
481 In this study, the model was used to assess the effects of crop residue mulching on crop
482 productivity and its sustainability, but the model could potentially be used to explore the
483 effects of other modes of management of crop residues such as compost production or the
484 introduction of fodder crops grown in rotation or in association with maize. Fodder crops can
485 favor synergies between feeding livestock and maintaining soil fertility through biomass
486 and/or nitrogen additions when they are legume species (e.g. Andriarimalala et al., 2013).
487 Further research with AMBAWA may help to identify improved biomass management with a
488 portfolio of practices instead of solely crop residue management as it was done in this first
489 application of AMBAWA.

490

491 **4.2 Limits and potential improvements of the AMBAWA model**

492 With AMBAWA, we followed the parsimony principle, which says that 'models should be as
493 simple as possible but as complex as necessary for the specific modelling objective, and not
494 be overloaded with unnecessary details, and have minimum data requirements' (Adam et al.
495 2012). The development of the AMBAWA model followed a classic approach where layers of
496 complexity are built step by step from a simple conceptual model. In our study, a computer
497 scientist worked closely with agronomists by iterating feedback loops of model
498 conceptualization-implementation-coding-testing (Le Page, 2017). Despite being based on
499 empirical data gathered in the village of Koumbia (Diarisso et al. 2015a, Diarisso et al.
500 2015b), the model does not represent the spatial peculiarities of the study area. In its current

501 form, AMBAWA is not a pure abstract theoretical model (KISS; Keep It Simple and Stupid),
 502 nor a realistic empirical model describing all processes at stake (KIDS; Keep It Descriptive
 503 and Stupid), but it is located in an ‘in between’ zone as identified by Sun et al. (2016), i.e the
 504 KILT approach (Keep It a Learning Tool, Le Page and Perrotton, 2017) (Figure 6). The KILT
 505 approach offers an alternative to the dichotomist vision of theoretical versus empirical
 506 models. The stylized KILT-type models focus on the co-construction of alternatives with
 507 stakeholders, and therefore should not be too complicated, nor too simplistic as they need to
 508 be able to offer realistic simulations to co-build alternative farming systems. In its current
 509 form, AMBAWA falls exactly into this category of model.



510
 511 Figure 6: The position of the AMBAWA model within the diagram of ‘utility’ of simulation
 512 models as a function of ‘complexity’. Red, purple and blue lines represent the utility function
 513 of the abstract, stylized and realistic models, respectively. Arrows represent the driving forces
 514 of both KISS and KIDS approaches (Le Page and Perrotton, 2017, adapted from Sun al al.,
 515 2016).

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

518

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

522 With the current model, once crop residue sources are depleted, the cattle instantaneously
523 leave the village to search for other sources of feed. In reality, in the study region alternative
524 feed sources are used when biomass scarcity occurs in the middle of the dry season. One of
525 them, which could be included in the model, is the use of cottonseed cake, a well-known by-
526 product of cotton production. Even if cottonseed cake is costly, it can constitute a significant
527 share of the feed ratio of cattle, of up to 130 kg TLU⁻¹ yr⁻¹ (Vall et al., 2006). Additionally, an
528 improved version of the model could incorporate more complex processes such as variable
529 cattle feed intake rates throughout the year, with for example low daily fodder needs during
530 stress periods (Assouma et al., 2018), and more accurate zootechnical data such as the ratio of
531 faeces produced at night which appeared as a sensitive parameter in the model (Figure 2).
532 Lastly, an important aspect on the livestock system to be considered concerns the manure
533 quality, as all manure in the AMBAWA model is considered to have the same quality, i.e. the
534 same fertilization potential. It has been observed that quality of manure in mixed crop-
535 livestock smallholder systems in sub-Saharan Africa can vary greatly (Rufino et al., 2007).
536 For example, the manure deposited in the parks, mixed with surface soil through cattle
537 trampling (“poudrette”), loses a large amount of its nitrogen content in comparison with the
538 manure directly deposited on the fields during crop residue free grazing (Ganry and Badiane,
539 1998). Hence, nitrogen inputs from manure produced in parks may have been overestimated
540 in AMBAWA.

541 The cropping system is also deliberately simplified in AMBAWA but further development of
542 the model could include more accurate empirical-based rules and equations. For example, the
543 cropping calendar is fixed in the current version of the model while different farmers adopt

544 different practices and different sowing or harvesting dates, in particular to cope with whether
545 variability or with pests and diseases (Madege et al., 2018). At village scale, this diversity of
546 cropping calendars will potentially entail different biomass flow patterns and possibly new
547 synergies between farmers (e.g. an early crop in a relay-intercropping system could generate
548 fodder during the rainy season). Finally, simulation of soil fertility can certainly be improved
549 in the model, e.g. through simulating soil organic matter dynamics and its impact on crop
550 yields. Ultimately, such improvement could be implemented by coupling AMBAWA to an
551 existing process-based crop model (e.g. DSSAT, Jones et al. 2003; STICS, Brisson et al.,
552 2003; APSIM, Keating et al., 2003). Amongst others, this coupling would require daily data
553 on temperature and rainfall, instead of a simple description of the season in two periods.
554 However, we would like to emphasize here that the complexity included in simulation models
555 should go with the specific research question addressed (Passioura, 1996).

556

557 **4.3 Perspectives for the use of the AMBAWA model**

558 Although refinements of AMBAWA could be envisaged (see section 4.2), the model in its
559 current state permits to simulate the differentiation of crop productivity among farming
560 systems under the current free-grazing rules in an agro-pastoral area. Highest yields were
561 simulated for livestock owners due to transfer of manure to their fields. Such transfers of
562 fertility that results from cattle ownership and management have been described previously
563 (Manlay et al., 2004; Diariosso et al., 2015a, 2015b; Vall et al., 2006), but were never
564 explored through simulation modelling. Compared to current whole-farm models, such as
565 Cikedda (Sempore et al., 2015) or FarmSim (van Wijk et al., 2009) that were used for the
566 analysis of the impact of innovative agricultural practices on crop productivity at farm level,
567 AMBAWA also considers the effect of innovative practices, including the interactions
568 between farmers, on the restitution of manure by animals. Compared to an existing model that

569 explores impact of agricultural land use in West Burkina Faso at field and farm scales (Jahel
570 et al., 2017), AMBAWA also simulates livestock systems and their mobility, a key
571 component of farming system resilience in the agro-pastoral areas of Burkina Faso.
572 Consequently, AMBAWA contributes to existing agent-based models that assess the
573 complexity of agricultural systems (e.g. Schreinemachers and Berger, 2011; Belem et al.,
574 2011; Rasch et al., 2017, Grillot et al., 2018a, 2018b) but with a specific emphasis on the
575 management of crop residues that are a key resource in the smallholder systems of West
576 Africa. It has been emphasized that there is an urgent need to improve soil fertility (Stewart et
577 al., 2020) without exposing conflicts between crop farmers and pastoralists (Andrieu et al.,
578 2015) through defining collectively rules and land charters for crop residue collection (Dabire
579 et al., 2017). AMBAWA can consequently be a useful discussion tool for stakeholders
580 (farmers, traditional and administrative authorities) involved in the management of crop
581 residues at the village level in order to co-design differentiated scenarios for sustainable use
582 of collective resources.

583 Finally, AMBAWA has already been presented in various scientific events (Berre et al.,
584 2019), in new research projects where it will be used (DSCATT, <https://dscatt.net/>; 3F,
585 <https://www.ccrp.org/grants/3f/>), and raised exciting discussions on soil fertility management
586 and crop-livestock integration using interactive model simulations. In a close future, the
587 model will be adapted to interact with farmers and enrich the socio-economic component of
588 the model, for instance as a ‘serious game’ (Michalscheck et al., 2020) on biomass flows at
589 village scale. For example, serious board games (in which farmers decide to growth certain
590 crops and allocate livestock to grazing areas according to external information such as climate
591 or market prices) will allow generating co-learning cycles through which farmers learn about
592 the impact of their decisions on soil fertility patterns at farm and village scale, and through
593 which researchers will better understand drivers of farmers’ decisional processes.

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599

600 **6 Conclusions**

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

615

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