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A methodology based on territorial metabolism analysis to assess the multi-criteria sustainability of African village terroirs with contrasted crop-livestock systems

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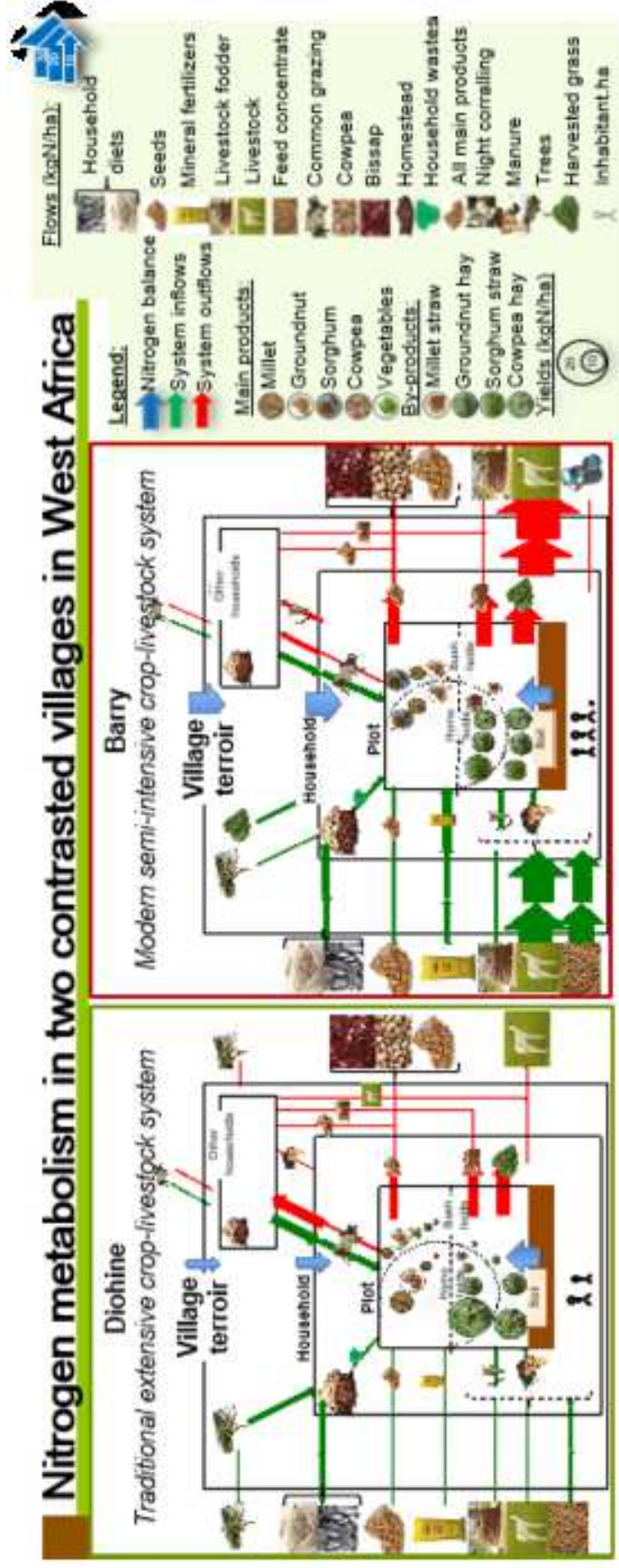
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Abstract

CONTEXT

Agricultural intensification to ensure food security and limit rural exodus is a major issue in sub-Saharan Africa. The potential of livestock farming to improve the sustainability of farming systems has been studied but rarely at the landscape level. However, because the herds move about in the landscape, thereby creating horizontal biomass and nutrient flows between plots and households, the landscape is the only level where all the interactions between the different components of the agro-ecosystem (animals, crops and trees) can be taken into account.

OBJECTIVE

Our objective was to develop a methodology that uses territorial metabolism for multicriteria assessment of sustainability to compare contrasted livestock systems.

METHODS

We compare two neighboring village *terroirs* in the former groundnut basin of Senegal. One village (Diohine), has kept a “traditional extensive system” based on fallow, free grazing and night corralling, while the other (Barry) uses a “modern semi-intensive system” based on livestock fattening in which the livestock is stall-fed with feed concentrate and crop residues. Village households were surveyed to describe their practices and to quantify biomass and nitrogen (N) flows to calculate sustainability indicators (productivity, balance, efficiency, dependency, profitability) at plot, household and village *terroir* levels.

RESULTS AND CONCLUSIONS

At village *terroir* level, introducing livestock fattening increased the livestock stocking rate (cf. 0.96 TLU.ha⁻¹ in Diohine and 2.31 in Barry) and spreading of solid manure on crop fields (respectively 337 and 482 kgDM ha⁻¹). Fattening livestock requires large imports of feed concentrate, 23.67 kgN ha⁻¹ in Barry versus 3.39 kgN ha⁻¹ in Diohine. The improved livestock productivity of fattening (+217 kgLW ha⁻¹) produces higher financial returns (+432€ household⁻¹ year⁻¹) that enable higher volumes of mineral fertilizers (6.28 kgN ha⁻¹ in Barry versus 1.09 in Diohine). The additional N inputs in Barry enable increased yields of the main staple crop (millet) (+101 kgDM ha⁻¹). The population density of Barry village is +78% higher (320 capita km⁻² in Barry versus 180 in Diohine). The village nitrogen balance (24.88 kgN ha⁻¹ in Barry versus 8.51 in Diohine) and N use efficiencies (respectively 0.64 and 0.15) demonstrate that nutrient cycling and soil fertility management are more sustainable in Barry.

SIGNIFICANCE

We propose a methodology to rebuild territorial metabolism from surveys. Territorial metabolism is used to calculate a set of multi-criteria sustainability indicators. This methodology will be particularly useful in Southern countries where data on agricultural systems are lacking.

1 **A method based on territorial metabolism analysis to assess the multi-criteria**
2 **sustainability of African village terroirs with contrasted crop-livestock systems**

3

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18

19 **Abstract**

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21 **Graphical abstract**

22

23 **Key words:** territorial metabolism, nutrient cycling, village *terroir*, agro-sylvo-pastoral
24 systems, livestock fattening, Senegal

25

26 **1. Introduction**

27 In West Africa, improving living standards and food security are still key issues
28 (Lahmar et al., 2012). In sub-Saharan Africa in 2012, poverty still affected more than half the
29 population, with 40.3% of the inhabitants earning less than US\$2.15 per day, especially in rural
30 areas, which account for 63% of the total population) (The World Bank, 2012a, 2012b). The
31 sustainability of agricultural systems is a major concern since most of the population is rural.
32 Integrated agro-sylvo-pastoral systems have traditionally predominated in West Africa (Dugue
33 et al., 2012; Jouve, 2001). These systems are based on the complementarity between ruminant
34 herds, cereal crops, and wooded parklands (Jouve, 2001) and their sustainability depends to a
35 large extent on fertility transfers from rangelands to cropped lands, through herd mobility and
36 night corralling (Dugue, 1985; Freschet et al., 2008). The high population growth rate (above
37 +2.4% per year in sub-Saharan Africa since 1961) led to a rapid change in agricultural systems
38 (Dongmo et al., 2012; The World Bank, 2023), when rural populations started to crop
39 rangelands (Courtin and Guengant, 2011; Faye and Landais, 1986) and reduce fallow (Andrieu
40 et al., 2015; Serpantie and Ouattara, 2001) to meet their food needs, thereby decreasing fodder
41 resources while increasing pressure on wooded parkland. Wooded parklands have been
42 overused during droughts, resulting in their decline (Courtin and Guengant, 2011; FAO 2003).
43 As a consequence, herds have become smaller and livestock is fed with crop residues (Andrieu
44 et al., 2015). Farmers progressively have appropriated crop residues for sale or stored them to
45 feed their livestock in the dry season (Dugue, 1985; Schlecht et al., 2004). This shift in behavior
46 reflects the transition from a collective management system to an individual management
47 system and stresses tensions surrounding biomass resources (Courtin and Guengant, 2011;
48 Jouve, 2001). Finally, export of the biomass produced in the fields (the main crop products plus
49 the crop residues) combined with continuous cropping has led to soil fertility depletion since
50 nutrient exports are no longer offset by an equivalent supply of livestock manure (Andrieu et
51 al., 2015; Buldgen et al., 1992). This phenomenon led to a reduction in crop yields because
52 soils in West Africa are inherently poor in nitrogen and organic matter (Schlecht et al., 2004).

53 Some studies have shown that the intensification of livestock farming combined with
54 crop-livestock integration can address these issues. This strategy can increase farm scale
55 sustainability from both an environmental (Alvarez et al., 2014; Bénagabou et al., 2017) and an
56 economic perspective (de Ridder et al., 2015; Duncan et al., 2013). The vast majority of studies
57 focused on the farm level, and few analyzed this livestock-based strategy at plot, farm (here the
58 household) and landscape (here the village) levels simultaneously.

59 Landscape is the level of analysis at which all the interactions between ecosystem
60 components (livestock, crops and trees) can be taken into account, since in sub-Saharan Africa,
61 herds move around in the landscape thereby creating spatial and horizontal biomass and nutrient
62 flows (Bisson et al., 2019; Manlay, 2001). The agricultural landscape in sub-Saharan Africa is
63 organized in village *terroirs*. The Africanist concept of *terroir* has been defined as the « area
64 cropped and exploited by a village community » (Rabot, 1990). A *terroir* is also defined as a
65 space with social and geographical features that contains the community's resources and
66 associated rights to satisfy their needs (Bernard, 2015). In West Africa, village landscapes are
67 traditionally structured in four concentric rings corresponding to land units (Manlay et al., 2004).
68 Starting from the center and moving toward the periphery, they comprise: (i) the dwelling, i.e.
69 the homestead; (ii) “home fields”, i.e. those closest to the homestead, where organic matter is
70 concentrated in order to insure food security through the production of staple foods; (iii) “bush
71 fields”, where cash crops are usually grown and where fallow land is used for livestock
72 corralling and grazing during the cropping season; (iv) “rangelands”, which form the outermost
73 ring of the village land, and are often less fertile.

74 In many West African ethnic groups, family members are gathered together in a ‘holding’.
75 Each holding is a dwelling unit grouping several household. Whereas historically, most of the
76 decisions were made at the scale of the holding, today, due to individualization, the household
77 is the usual decision-making unit concerning agricultural resources (herd, land, machinery, etc.)
78 (Adjamagbo et al., 2006). Distinguishing types of households with different strategies and
79 practices makes it possible to account for interactions (e.g. biomass flows) between households
80 and to better explain village-level performance (Andrieu et al., 2015). For instance, agreements
81 between households can improve biomass management and nutrient transfers in village *terroirs*
82 (Diarisso et al., 2015).

83 Finally, the plot represents the crop management unit, i.e. the level where crop
84 management practices are implemented. For instance, night-corralling means a herd is parked
85 in a particular plot for a specified length of time leading to biomass and nutrient livestock-
86 driven flows between plots (Grillot et al., 2018a). Conventionally, the plot is the level

87 considered to assess the sustainability of cropping systems. For instance, yields and fertility
88 balances are assessed at plot level (Schlecht and Hiernaux, 2004).

89 In this study, we implemented a multi-level (plot, household, village) biomass and
90 nutrient flow analysis to calculate multiple indicators and to compare two neighboring village
91 *terroirs* located in the groundnut basin of Senegal. The groundnut basin of Senegal is widely
92 known for its agricultural intensification dynamics. The groundnut basin has undergone
93 spectacular demographic growth (Delaunay et al., 2013); in the 1960s, the region already
94 seemed saturated (Lericollais, 1999), nevertheless between 1963 and 2009, the population of
95 the region doubled (Delaunay and Lalou, 2012). The strategies used by the villages to adapt to
96 this land pressure have been contrasted. In order to keep livestock in the *terroirs*, some of the
97 village communities kept common fallow and free-grazing systems, whereas other
98 communities developed livestock fattening systems based on the purchase of feed concentrate
99 (Audouin et al., 2015). The Senegalese groundnut basin is representative of the intensification
100 dynamics that are predicted for the next two to four decades in West Africa (Vayssières et al.,
101 2015).

102 This study assesses the consequences of livestock intensification for the functioning and
103 sustainability of two neighboring village *terroirs* with similar soil and climate conditions, but
104 characterized by contrasted livestock systems: free grazing versus livestock fattening systems.
105 To this end, a multi-criteria assessment of the two village *terroirs*' sustainability was
106 undertaken based on environmental (nitrogen balance and nitrogen use efficiency), technical
107 (crop and livestock productivity), social (dependency) and economic (agricultural income and
108 gross margin) indicators.

109 **2. Description of the study area, methods, and techniques**

110 **2.1. Study area and the village *terroirs***

111 This study focused on two village *terroirs* located 8 km apart in the former groundnut
112 basin: Diohine (14°30'15.682N; 16°30'8.763W) and Barry (14°34'29.905N; 16°29'18.364W).
113 Both form part of Niakhar health, demography and environment observatory, one of the oldest
114 observatories in sub-Saharan Africa (Delaunay et al., 2013). Most inhabitants belong to the
115 *Serer* ethnic group (95.2% in Diohine; 88.5% in Barry). Islam is the main religion (47.7% in
116 Diohine; 98.1% in Barry) followed by Christianity (Delaunay et al., 2013).

117 The main types of soil are luvic Arenosols and ferric Luvisols (Tschakert, 2004). Local
118 stakeholders differentiate two main soil types: “*dior*” and “*deck*” soils. “*Dior*” soils account for
119 70% of the area, they are mainly composed of sand (> 95%), have low organic matter content

120 (< 0.2%) and low nitrogen content (< 0.1%). “*Deck*” soils are slightly hydromorphic with high
121 sand content (85–90%), 3-8% clay, 2% silt, 0.5-0.8% organic matter content, and 0.2-0.4‰
122 nitrogen content (Badiane et al., 2000).

123 The climate is semi-arid, Sahelian-Sudanese, with 566-mm year⁻¹ average rainfall (mean
124 rainfall measured at Fatick weather station from 2000 to 2012), a short wet season from June
125 to September and a long dry season divided into two seasons: a cool dry season from October
126 to January and a hot dry season from February to May.

127 Both the agricultural systems are rainfed and the main crop grown is millet (*Pennisetum*
128 *glaucum*) and groundnut (*Arachis hypogaea*) using animal traction (Badiane et al., 2000).
129 Secondary crops are sorghum and cowpea (Tschakert, 2004). The main livestock species are
130 cattle (*zebu gobra*), small ruminants (sheep and goats), and horses and donkeys (used as draught
131 animals) (Lericollais, 1999). The main feature of the village of Diohine is its traditional
132 agricultural system based on collectively managed fallows, free grazing and night corralling in
133 crop fields. The main features of the village of Barry are continuous cropping and livestock
134 fattening in barns based on purchased feed concentrate and harvested crop residues. Figure 1
135 shows that livestock fattening is practiced by the large majority of households in the village of
136 Barry but rarely practiced in Diohine.

137 *Figure 1 about here*

138

139 **2.2. The conceptual model of the socio-agro-ecosystem studied**

140 Metabolism is a key concept in industrial ecology. The analysis of industrial metabolism
141 (Wassenaar, 2015), or territorial metabolism (Barles, 2014), is largely based on the
142 quantification of material flows to describe the functioning of existing territories and to design
143 more sustainable territories. This approach has already been used to analyze rural territories
144 (Bonaudo et al., 2017). The analysis of biomass flows is particularly useful to understand how
145 complex agricultural systems function and to assess their sustainability (Vayssières et al., 2009).
146 Integrated landscape analysis distinguishes multiple levels (Minang et al., 2015). The present
147 study of village *terroirs* is based on a stock-flow conceptual model structured around three
148 interlocked systems: the plot, the household, and the village *terroir* (Figure 2). The village is
149 composed of several households, and each household can be divided into four subsystems: the
150 family, crops and trees, livestock, and organic waste (Figure 2). Livestock usually comprises
151 several herds.

152

153 *Figure 2 about here*

154

155 The systems are crossed by biomass flows corresponding to the main types of organic
156 matter circulating within and between farming systems, i.e. crop products (grain, residues, etc.),
157 livestock (dung, meat, milk, etc.), trees (forage, wood, etc.), as well as household purchases
158 (human food, feed concentrate, mineral fertilizers, etc.). Three types of biomass flows are
159 distinguished: inputs, outputs and internal flows. Some outflows at one level (e.g. the plot) are
160 internal flows at a higher level (e.g. the household; Figure 2).

161 **2.3. Data collection and processing**

162 **2.3.1. Household sampling and survey**

163 Data were collected during household surveys conducted from June to August 2013 and
164 concerned the 2012 cropping season (from June 2012 to May 2013). The exhaustive list of the
165 households in each village and the population data were extracted from the Niakhar observatory
166 data base (Delaunay et al., 2013). The surveys in Barry were exhaustive (73 households) but
167 were conducted on a sample of 44 households, corresponding to the *Sassem* district. In Diohine
168 which is a large village containing 354 households, the districts are regulated by notables who
169 are responsible for the management of the natural resources (e.g. the common fallow). *Sassem*
170 district is representative of Diohine's agricultural activities, practices and access to resources.
171 Consequently, the observations and analysis of this district presented in this paper can be
172 considered as representative of the whole village of Diohine.

173 The aim of household surveys is to describe the structure and agricultural practices of
174 each household and to quantify all household biomass flows, i.e. flows of inputs and outputs to
175 and from all households, plus flows of inputs and outputs to and from the four subsystems
176 (family, crops and trees, livestock, organic waste) of each household (Figure 2).

177 **2.3.2. Computing biomass flows**

178 Biomass flows can be human driven or herd driven (ingestion during grazing and
179 excretion during grazing and night-corralling). Human driven flows were directly quantified
180 with farmers during surveys using local units of measure (cart, bundle, etc.). These flows were
181 then converted into standard units (kgDM). Conversion factors were defined by weightings
182 made during the study or based on data in the literature (Vandermeersch et al., 2013, Appendix
183 1).

184 Herd-driven flows were derived from information concerning herd feeding practices
 185 and the time spent between the four land units within the boundaries of the village *terroir*
 186 (dwelling, home fields, bush fields, rangelands) collected during the surveys. Herd-driven flows
 187 were calculated (in kgDM season⁻¹) for each practical season (wet season, cool dry season, hot
 188 dry season) defined in section 2.1 above. Free-grazing animals ingest the biomass available in
 189 plots: crop residues in cultivated fields after harvest and grass growing on common fallow land
 190 and rangelands all year round. Part of the biomass is returned to the soil via animal excreta.
 191 Both ingestion and excreta flows were calculated based on coefficients derived from local
 192 observations (Wade et al., 2017) or on data available in the literature on West Africa (Appendix
 193 2 and 3).

194 Between-household livestock-driven plant biomass flows were described for each
 195 household by calculating the free-grazing plant biomass balance (ΔFG) corresponding to the
 196 difference between (i) inflows by means of intakes by the household herd on external plots
 197 (AII) and (ii) outflows by means of intakes by external herds on household plots (AIO).

$$\Delta FG = AII - AIO \quad (1)$$

198 AII and AIO were both calculated according to the fodder biomass available for each household
 199 (AFB) as follows:

$$AFB = ((FP_{p,c} - FH_{p,c}) * C_c) - FN_b \quad (2)$$

$$\text{If } AFB = 0 \text{ then } AII = 0 \text{ and } AIO = 0 \quad (3)$$

$$\text{If } AFB > 0 \text{ then } AII = 0 \text{ and } AIO = AFB \quad (4)$$

$$\text{If } AFB < 0 \text{ then } AII = -AFB \text{ and } AIO = 0 \quad (5)$$

200 where FP_p and FH_p are respectively the fodder produced and the fodder harvested per plot p
 201 defined by the household's practices. C_c is a consumption coefficient per type of crop c since
 202 crop residues are not completely consumed by the livestock. FN_b is the quantity of crop residues
 203 needed for each batch b of animals belonging to the household. The quantity of crop residues
 204 required is calculated based on the size of the batch, the feeding practices of each batch and the
 205 standard forage intake per TLU (Appendix 2).

206 Excretion flows between households are described for each household as (i) the amount of
 207 excretion by the household herd on external plots (AEO in kgDM season⁻¹) and (ii) amount of
 208 excretion by the external herd on plots belonging to the household in kgDM season⁻¹). They are
 209 calculated as follows:

$$AEO = (LU_{b,I} * AT_{b,I} * DR) * (TA_I - A_I) / TA_I \quad (6)$$

$$AEI = (LU_{b,I} * AT_{b,I} * DR) * (A_I) / TA_I \quad (7)$$

210 where LU_b and $AT_{b,I}$ are respectively the size of the batch of animals **b** (in TLU) and the length
 211 of time (in hours) spent by each batch of animals **b** in the landscape concerned, unit **I**. DR is
 212 the deposition rate (in $kgDM\ TLU^{-1}\ hour^{-1}$). A_I is the area of the household's landscape unit **I**
 213 considered. TA_I is the total area of the landscape unit **I** in the village *terroir* considered. The
 214 same two equations (equ. 5 and 6) are applied for urine and dung with their corresponding
 215 deposition rates DR (Appendix 3). Deposition rates and nitrogen content vary with the season
 216 (Appendixes 3 and 4).

217 **2.3.3. Household typology**

218 To build the household typology, a set of 42 parameters was collected from the 117 households
 219 These parameters were grouped in three categories: parameters that concern the farming
 220 features that inform the intensity of crop and livestock activities, i.e., total cultivated area (TCA),
 221 farm equipment, livestock stocking rate, fattened livestock fattening stocking rate, groundnut
 222 and fallow TCA rate inflows and outflows); parameters that concern the family (e.g. number
 223 of household members, age of the household head, number of spouses); the impacts of farming
 224 practices (i.e. nitrogen and nitrogen use efficiency livestock balances (§ 2.4), free-grazing
 225 biomass and excreta balances, night corralling balances).

226 Household types were determined by cluster analysis and included the following steps: (i) a
 227 principal component analysis was performed on the set of variables, (ii) a hierarchical cluster
 228 analysis was conducted using Ward's method.

229 The principal component analysis procedure (step i) sought uncorrelated linear combinations
 230 (components) of the original variables. Then, meaningful variables were identified from the
 231 loadings that measured the contribution of each original variable to the variance of the principal
 232 component.

233 The hierarchical partitioning (step ii) sought to build clusters using Ward's minimum variance
 234 criterion that minimizes total within-cluster variance.

235 The final typology represents diverse resource endowments and crop and livestock practices.
 236 All the households differ in size and in their crop and livestock activities, and the intensity of
 237 the practices varies according to the type of household. Five types of households were defined:
 238 Low Resource Endowment- Small Herd (LRE-SH), Medium Resource Endowment- Small

239 Herd (MRE-SH), Medium Resource Endowment- Medium Herd (MRE-MH), High Resource
240 Endowment- Medium Herd (HRE-MH), High Resource Endowment- Large Herd (HRE-LH).

241 **2.4. Sustainability indicators**

242 Nitrogen is a major limiting factor for agricultural productivity in sub-Saharan Africa,
243 (Rufino et al., 2009; Schlecht et al., 2006). Biomass flows (in kgDM year⁻¹) were converted
244 into nitrogen flows (in kgN year⁻¹) using conversion factors in the literature (Appendix 5). This
245 study assessed three N-based sustainability indicators: productivity, balance, efficiency at three
246 levels (plot, household, village *terroir*).

247 Household food security is a major concern on the entire African continent (FAO 2015).
248 The **productivity** of the agricultural systems is assessed for livestock in kgLW ha⁻¹ year⁻¹ and
249 for crops in kgDM ha⁻¹ year⁻¹. The productivity indicator is also expressed in kgN ha⁻¹ year⁻¹
250 and kgN capita⁻¹ year⁻¹ because sufficient protein availability in the human diet a major problem
251 in Africa (Duncan et al., 2013; FAO 2015).

252 The nitrogen **balance** (NB) is a relevant sustainability indicator for soil fertility (Manlay
253 et al., 2004; Roy et al., 2005; Thornton and Herrero, 2001). System-gate nitrogen balances were
254 calculated as follows:

$$\text{NB} = (\Sigma\text{IN} - \Sigma\text{ON}) / \text{TCA} \quad (8)$$

255 where IN and ON are, respectively, total nitrogen inputs and nitrogen outputs in the system
256 considered (plot, household or village *terroir*, see section 2.2.). The calculated balances are
257 partial balances, i.e. they only include horizontal (i.e. apparent) flows and not vertical flows of
258 N (gaseous emissions, symbiotic fixation, atmospheric deposition, lixiviation and run-off).

259 Nitrogen use **efficiency** (NUE, dimensionless, Dmnl) assesses the “return on investment”
260 since for each nitrogen unit supplied to the system, it indicates how many nitrogen units are
261 produced (Vayssières, 2012).

$$\text{NUE} = \Sigma\text{ON} / \Sigma\text{IN} \quad (9)$$

262 Agro-sylvo-pastoral systems in sub-Saharan Africa are traditionally low-input systems
263 based on the use of natural resources (Vigne et al., 2013). Agricultural intensification is often
264 based on inputs that considerably modify the system’s **dependency** on external systems.
265 Dependency corresponds to imports into the system (in kgN capita⁻¹ year⁻¹, (Rufino et al., 2009).
266 This indicator represents household self-sufficiency (SS) in terms of herd feeding (SSFeed),
267 and in terms of crop fertilization (SSFert). SSFeed (dmnl) is the fraction of the N feed in the
268 herd feed ration produced on the farm. SSFert (dmnl) is the fraction of the plot IN fertilizers

269 originating from organic fertilizers produced on-farm (Vayssières et al., 2011). A second
 270 indicator, **dependency (D)**, only calculated at the village *terroir* level is the ratio of total
 271 nitrogen inputs (**IN**) to the total system throughflow (**TST**). Total System Throughflow is
 272 calculated as the difference between the sum of a household's IN flows and village *terroir* IN:

$$D=IN/TST \quad (10)$$

$$TST=\sum IN_h - IN_t \quad (11)$$

273 Household livelihoods are expressed by two economic indicators: gross margin yield
 274 and agricultural income. The gross margin yield (GMY in € year⁻¹ ha⁻¹) is calculated as the
 275 gross margin (GM) per area unit, considering the HH TCA (in ha), as follows:

$$GMY=GM/TCA \quad (12)$$

$$GM= (MP_{cb} * MPr_{cb}) - (MS_{cb} * MPr_{cb}) \quad (13)$$

276 where MP_{cb} and MS_{cb} are, respectively, the amount of biomass purchased and the amount of
 277 biomass sold per category of biomass **cb**. MPr_{cb} is the price of each category of biomass. The
 278 price of each input (mineral fertilizers, pesticides, seeds, human food, fuel, fodder, feed
 279 concentrate, number of animals) and outputs (wood, fodder, main crop products, milk, number
 280 of animals sold or given away) was collected during the surveys. The price obtained for an
 281 animal depends on its physical condition: fattened animals from in-barn herds fetch higher
 282 prices than animals from free-grazing herds (Appendix 6).

283 The agricultural income (AI in € year⁻¹) also includes additional fixed costs:

$$AI= GM - [Nb_e \times (MC_e + DC_e)] \quad (14)$$

284 where MC_e and DC_e are maintenance costs and depreciation, respectively. These cost are listed
 285 for each type of farm equipment **e** (Appendix 7).

286 At plot level, non-parametric statistic tests were performed on village *terroir*
 287 independent samples. Student's t test, Fisher's F test were performed to see if the results differed
 288 significantly. The Mood test was used to compare medians of k independent samples. This test
 289 makes no assumptions concerning the distribution of the measurements- and can be considered
 290 as a special case of the Pearson Khi² test.

291 **3. Results**

292 **3.1. Organization of the two village terroirs**

293 **3.1.1. Spatial organization**

294 Diohine is an old village whose dwellings are concentrated and organized in districts.
295 The dwellings in Barry are fragmented and dispersed as a result of multiple waves of population
296 arrivals. Diohine is consequently governed by a “district hierarchy” while Barry is characterized
297 by a strong “holding hierarchy”.

298 Diohine’s *terroir* is surrounded by 67 ha of lowlands that represent 24% of the total area
299 of the village *terroir*) and have traditionally been used as rangelands that insure the free-grazing
300 herds do not need to leave the village *terroir*. Conversely, Barry *terroir* has no lowlands, ponds
301 or wooded savannah within its traditional boundaries (Figure 3).

302 *Figure 3 about here*

303 **3.1.2. Humans, livestock and land use**

304 Human population pressure is lower (180 capita km⁻²) in Diohine than in Barry
305 (320 capita km⁻²) as is the livestock stocking rate (0.96 TLU year ha⁻¹ in Diohine compared
306 with 2.31 TLU year ha⁻¹ in Barry). In Diohine, an extensive livestock system still exists. Based
307 on traditional rules, each year, 20% of the TCA is kept as fallow for grazing in the wet season.
308 Barry has only a few isolated fallow plots resulting from decisions made by individual
309 households following failed cropping.

310 Millet is still the main crop in both village *terroirs*, where it represents 53% of the TCA
311 in Diohine and 55% in Barry. Groundnuts represent only 7% of the TCA in Diohine whereas
312 in Barry they represents 30%.

313 **3.1.3. Household diversity**

314 Households in both villages were classified in five types. The main discriminant
315 variables were the ratio of livestock to cropping activities (i.e., the livestock stocking rate)
316 and the relative importance of subsistence and cash crop and livestock activities (Table 1).

317 *Table 1 about here*

318 Two of the household types use extensive and subsistence oriented systems: the “Medium
319 Resources Endowment-Small Herd” (MRE-SH, type 2) and the “High Resources Endowment-
320 Medium Herd” (HRE-MH, type 4). Both household types have large fallow land and large free-
321 grazing herds; only a small percentage of the herd is fattened (on average 15% of the herd in
322 type 2 and 3% in type 4). These two types of household depend on their *terroir*’s communal
323 resources (crop residues, fallows and rangeland fodder, and wooded parkland). Type 4 is only
324 represented in Diohine, and more type 2 are found in Diohine than in Barry.

325 Two of the household types are semi-intensive and cash oriented systems: the “Medium
326 Resource Endowment- Medium Herd” (MRE-MH, type 3) and the “High Resource
327 Endowment- Large Herd” (HRE-LH, type 5). Both focus on commercial production (groundnut
328 and livestock fattening) and both types are only represented in Barry. The proportion of
329 livestock fattening activity is higher in type 5. Type 5 also supports the highest human
330 population density (6.3 capita.ha⁻¹; Table 1).

331 The “Low Resource Endowment- Small Herd” (LRE-SH, type 1) comprises households with
332 limited TCA (average: 3.8 ha) and few livestock. Type 1 is involved in intensification, and
333 trying to invest in groundnuts and/or livestock fattening. This type is the second most common
334 type, and is more frequent in Barry where household individualization is more dynamic (Table
335 1).

336 Two household types are particularly involved in livestock rearing: type 4 in Diohine and type
337 5 in Barry. The average livestock stocking rate is 3.6 TLU ha⁻¹ under type 4 and 3.7 TLU ha⁻¹
338 under type 5. HRE-MH (type 4) fatten almost none of their livestock (3% of total TLU) and
339 mostly practice free grazing. Conversely, HRE-LH (type 5) fatten 59% of their herd. The
340 animals are kept in barns and are stall-fed with feed concentrate and harvested crop residues.

341 Analysis of household biomass flows showed that the majority of crop residues
342 produced on-farm are grazed (type 4) or harvested (type 5) to feed the herds. The Δ FG of HRE-
343 MH (type 4) was positive (3451 kgDM ha⁻¹ year⁻¹), showing that household herds consume
344 forage in plots belonging to other households, particularly plots belonging to MRE-SH (type 2)
345 who have a low livestock stocking rate and a negative Δ FG (-225 kgDM ha⁻¹ year⁻¹). HRE-MH
346 (type 4) thus benefits from these biomass transfers with the highest dung inputs taking place
347 during night corralling (+758 kgDM ha⁻¹). Similarly, type 5 buys crop residues (mainly
348 groundnut hay) from types MRE-SH (type 2) or LRE-SH (type 1), meaning types 4 and 5
349 extract nutrients from plots belonging to other households that are deposited on their own plots
350 thanks to night corralling (type 4) or through the spreading of solid manure (type 5). HRE-MH
351 (type 4) also provides night corralling to other households with limited manuring capacity (e.g.
352 type 1). According to traditional rules, this agreement gives type 4 the opportunity to borrow
353 external lands the following year (Odrú, 2013).

354 **3.2. Farming systems**

355 **3.2.1. Crop-livestock coordination across seasons**

356 Livestock farming and cropping practices in the two villages can be described based on
357 their seasonal practices (Figure 4).

358 *Figure 4 about here*

359 During the cropping season, i.e. the wet season and the beginning of the cool dry season,
360 livestock can damage crops. Consequently, some of the ruminants (bovine, ovine, goats) are
361 removed from the village *terroir* for transhumance to sylvo-pastoral regions of Senegal, for
362 example, the Saloum and Ferlo regions. The remaining livestock are kept away from crops in
363 the lowlands and common fallows in Diohine (Figure 3). As a result, Diohine supports a bigger
364 free-grazing herd during the wet season than Barry (0.56 TLU ha⁻¹ in Diohine versus 0.35 TLU
365 ha⁻¹ in Barry). On the other hand, Barry strongly invests in livestock fattening (0.57 TLU ha⁻¹
366 in Barry versus 0.01 TLU ha⁻¹ in Diohine;). This livestock system reduces direct interactions
367 between livestock and cropping since the livestock are kept in barns within the holding and a
368 large proportion of the feed ration is supplied in the form of harvested crop residues and feed
369 concentrate (e.g. complete concentrates, millet bran, rice bran) purchased outside the village
370 *terroir*.

371 During the second part of the cool dry season and in the hot dry season, as the main crop
372 products have been harvested, livestock can move freely throughout the whole village *terroir*.
373 Free-grazing ruminants start to consume crop residues left in the fields and at night, are
374 corralled on selected plots. In Diohine, during the cool dry season, free-grazing herds graze
375 crop residues on plots in home fields, where the residues are more abundant. During the first
376 part of the hot dry season, herds free-graze crop residues in bush fields and fodder resources in
377 the lowlands. During the second part of the hot dry season, herds consume crop residues stored
378 for the purpose by the farmers, who prune trees, mainly *Faidherbia albida*, for fodder (Odru,
379 2013).

380 The ovine fattening period targets Muslim religious events such as *Tabaski*, when the
381 demand for live sheep for sacrificial purposes is massive. Bovine fattening is spread out over
382 the entire dry season to produce off-season meat, which requires off-season labor and allows
383 farmers to take advantage of fluctuations in market prices. Diohine opted for “finishing” bovine
384 livestock fattening, i.e., some animals are extracted from the transhumance herds to be fattened,
385 whereas Barry opted for “purchase-resale” livestock fattening.

386 **3.2.2. Fertilization of cropland**

387 Herds' excreta (during free grazing or night corraling), solid manure and mineral
388 fertilizer inflows represent the three main N inputs to the plots. They total 83% of N input flows
389 (IN) at plot level in Diohine and 79% in Barry, the remainder being household waste, seeds and
390 feed refusals by livestock.

391

Table 2 about here

392 **3.2.2.1. Direct deposition of excreta during free grazing and night corralling**

393 The deposition of livestock excreta during free-grazing (excluding night corralling)
394 represents 46% of the total plot IN in Diohine versus 25% in Barry (Table 2). In the **dry season**,
395 in Diohine, a large proportion of by-products is left for **free-grazing** herds. In terms of N flows,
396 biomass extraction (crop residues or grass) is barely returned via feces and urine (the balance
397 of livestock-driven flows at plot level is on average +0.55 kgN ha⁻¹ Table 2). In contrast, in
398 Barry, the free grazing practice results in a positive balance of livestock-driven flows (on
399 average +5.04 kg N ha⁻¹ Table 2) since the livestock stocking rate is high and livestock feed is
400 supplemented with feed concentrate. Feed concentrates represent on average, 30% of the feed
401 ration in terms of N in Barry. Indeed, cash oriented households (MRE-MH and HRE-LH), two
402 types of households only represented in Barry, harvest most crop by-products on their fields
403 and supplement their animals' rations with feed concentrate, resulting in the highest free-
404 grazing and night corralling balance (+8.43 and +9.93 kgN ha⁻¹ for MRE-MH and HRE-LH
405 respectively, Table 1).

406 During the **wet season**, the common fallow practiced in Diohine results in a negative average
407 nitrogen balance in livestock-driven flows at plot level: -8.32 kgN ha⁻¹ (Table 2). Nevertheless,
408 the higher livestock stocking rate in Diohine than in Barry in the wet season, results in a higher
409 proportion of TCA benefitting from wet season **night corralling** (Table 2). The deposition of
410 excreta in the wet season is also more intensive in Diohine (Table 2). Conversely, in the **dry**
411 **season, night corralling** accounts for higher proportion of TCA in Barry and is more intensive
412 (Table 2).

413 **3.2.2.2. Application of solid manure**

414 Solid manure represents 14% of the total plot level IN in Diohine and 12% in Barry (Table
415 2). The average rate of solid manure application is higher in Barry (482 kgDM ha⁻¹) than in
416 Diohine (337 kgDM ha⁻¹) (Table 2). Furthermore, the households in Barry *terroir* are better
417 equipped with horse and donkey carts (86% of households in Barry own a cart versus only 48%
418 in Diohine). The higher equipment rate combined with higher solid manure availability results
419 in better spatial distribution of solid manure, since a larger proportion of the TCA is manured;
420 31% of the TCA is manured each year in Barry versus 22% in Diohine (Table 2).

421 **3.2.2.3. Application of mineral fertilizers**

422 Application of mineral fertilizer accounts for most of the plot inputs in Barry (27% of
423 IN in Barry versus 8% Diohine) (Table 2). Mineral fertilizers are applied to a bigger proportion

424 of the land in Barry (26% of the TCA) and fertilization is also more intensive, the average
425 application rate in Barry is more than five times higher than in Diohine (Table 2).

426 **3.3. Sustainability of the two village terroirs**

427 This section presents the main differences in the sustainability indicators at the level of
428 the village *terroir*. Indicators are sometimes also provided at household level to make the
429 differences between the villages more explicit.

430 **3.3.1. Productivity**

431 The yields of the main crops are significantly higher for cereals (millet and sorghum) in
432 Barry whereas groundnut yields are similar in the two villages (Table 3). With the exception of
433 legume hay, total yields of straw are substantially higher in Barry (Table 3). Farmers in Barry
434 harvest a bigger proportion of crop residues to stall-feed their own livestock (Table 3).

435 *Table 3 about here*

436 Meat production is 720% higher (252 kgLW ha⁻¹ year) in Barry than in Diohine
437 (35 kgLW ha⁻¹ year⁻¹). Total livestock sales and sales of crop-related products are much higher
438 in Barry (13 kgN capita⁻¹ in Barry versus 1 kgN capita⁻¹ in Diohine).

439 **3.3.2. Dependency**

440 Diohine inhabitants tend toward on-farm consumption and recycling of local biomass
441 resources (crop residues, dung and wooded parkland) while the inhabitants of Barry favor
442 exports-imports based on the use of inputs. Considering that the purchase of human food is
443 similar in the two villages (1.66 kgN capita⁻¹ in Barry and 1.62 kgN capita⁻¹ in Diohine), the
444 main difference in IN is due to the purchase of feed concentrate and mineral fertilizer, with
445 significantly higher inflows of this type in Barry (Table 4). Consequently, self-sufficiency rates
446 for feed and fertilizers are higher in Diohine (see SSFeed and SSFert in Table 4) resulting in a
447 lower dependence (D is 2.03 in Diohine versus 12.66 in Barry; Table 4).

448 *Table 4 about here*

449 **3.3.3. Nitrogen cycling, balance and efficiency**

450 Livestock farming activities play a determinant role in the functioning of both village
451 *terroirs* since they represent 52% of total crop fertilization IN flows in Barry and 75% in
452 Diohine (Table 2). As the livestock systems differ markedly in the two villages, flows linked to
453 free grazing (free-ranging deposition of excreta and plant withdrawal, deposition during night
454 corralling) are highest in Diohine (TST>IN, Table 4), while inflows and outflows linked to

455 livestock related (livestock, fodders, concentrate feeds) are highest in Barry (TST<IN) (Table
456 4).

457 Household practices and household functioning lead to higher nitrogen balance at village terroir
458 level (25 kgN ha⁻¹ for Barry and 9 kgN ha⁻¹ for Diohine) and to a higher average at household
459 level in Barry (24 kgN ha⁻¹) than in Diohine (13 kgN ha⁻¹). Households with livestock-oriented
460 farming system seem to have higher nitrogen balance at household level. For instance, MRE-
461 SH households (type 2) and HRE-LH households (type 5) have respectively the lowest and the
462 highest stocking rates (Table 1) and nitrogen balance at household level (-0.2 kgN ha⁻¹ and
463 151.0 kgN ha⁻¹ respectively).

464 At plot level, the average and median nitrogen balance at plot level do not differ significantly
465 between the two village *terroirs* (average nitrogen balances at plot level are -23 kgN.ha⁻¹ in
466 Barry and -20 kgN.ha⁻¹ in Diohine).

467 Flows in Barry are more intense with 7 times higher inflows (IN) and 35 times higher
468 outflows (ON; Table 4). Consequently, the NUE in Barry is 4 times higher than in Diohine at
469 the level of the village *terroir* (Table 4).

470 **3.3.4. Profitability**

471 The average household agricultural income (AI) is positive in both villages but is 19%
472 higher in Barry (2 292 € year⁻¹) than in Diohine (1 850 € year⁻¹). Households with limited
473 resources and small herds have the lowest agricultural income (1 028 € year⁻¹), while the highest
474 income is obtained by households with ample resources and large herds (3 795 € year⁻¹; Figure
475 5).

476 *Figure 5 about here*

477

478 Considering the gross margin yields, the average results are negative (-214€ year⁻¹ ha⁻¹
479 ¹). In contrast to AI, this calculation includes the purchase of human food. Different patterns
480 are observed depending on the type of household. Like AI, household with small herds have
481 the lowest gross margin yield (-415€ year⁻¹ ha⁻¹) while households with large herds and
482 sufficient resource endowment have the best results (-91€ year⁻¹ ha⁻¹; Figure 6).

483

Figure 6 about here

484 **4. Discussion**

485 **4.1. Traditional extensive systems face a number of limitations**

486 The results of this study are consistent with those of other studies on nutrient cycling in
487 sub-Saharan Africa. The nitrogen balance at plot level is generally negative: -23 kgN ha⁻¹ for

488 Barry and -20 kgN ha^{-1} for Diohine, and -15 kgN ha^{-1} on average for West Africa (Schlecht and
489 Hiernaux, 2004), range: -37 kgN ha^{-1} (Stoorvogel and Smaling, 1990) to 3 kgN ha^{-1} (Krogh,
490 1997), indicating that crop production depends to a large extent on mining the soil organic
491 nitrogen reserve (Smaling et al., 1997; Waneukem and Ganry, 1992). In the traditional
492 extensive system, nutrient exports were traditionally counterbalanced by livestock-based
493 nutrient transfers from rangelands and fallows to croplands (Bisson et al., 2019). But the
494 negative nitrogen balances indicate that these systems are no longer sustainable. When the
495 uncultivated area (fallows and rangelands) is too small, the nitrogen transfers generated by the
496 free grazing ruminants do not compensate for the export of crop biomass. This is the case in
497 Diohine where the livestock-driven nitrogen balance in common fallows is negative (§ 3.2.2.1).
498 From a social point of view, interviews indicated that the traditional system is likely to
499 disappear since the collective fallow system is very demanding in terms of social organization
500 and is called into question by different dynamics including household individualization (§ 1.).
501 This is consistent with the dynamics observed in other sub-Saharan contexts, for example, the
502 appropriation of the organic matter resource (Andrieu et al., 2015). In the new semi-intensive
503 systems (Barry), nutrient mining is offset by external inputs, mainly in the form of feed
504 concentrate in the livestock fattening system, which reintroduces nutrients in the households
505 and in the village *terroirs*.

506 **4.2. Livestock intensification seems to be a sustainable intensification pathway**

507 The main indicators of *terroir* sustainability are shown in a radial diagram (Figure 7) in
508 which the traditional system (Diohine) is the reference system. The sustainability of each
509 village *terroir* corresponds to the surface area delineated by the lines linking each indicator's
510 value. The semi-intensive system (Barry) is more sustainable, as the majority of indicators (7
511 out of 9) are higher for this village *terroir*.

512 The system based on livestock fattening is more efficient: nitrogen use efficiency (NUE)
513 is 4 times higher in Barry) and the nitrogen balance in Barry is positive and higher ($+16.37 \text{ kgN}$
514 $\text{ha}^{-1} \text{ year}^{-1}$ at the *terroir* level; Table 4). The livestock fattening-based system produces higher
515 average millet yields, millet being the main crop in both villages (Figure 7), i.e. an additional
516 $+101 \text{ kgDM ha}^{-1}$ of ears and $+595 \text{ kgDM ha}^{-1}$ of millet straw (§ 3.3.1).

517 *Figure 7 about here*

518 Gains in yields of crop residues and additional imported concentrate feeds ($+20.3 \text{ kgN ha}^{-1} \text{ year}^{-1}$
519 1 in Barry) support a higher livestock stocking rate (§ 3.1.2)., which, in turn, results in higher
520 organic matter availability and use in Barry ($+145 \text{ kgDM ha}^{-1}$). It also increases meat production

521 by +217 kgLW ha⁻¹. Meat sales produce an additional cash flow that is used for both crop and
522 household inputs (i.e. mineral fertilizer and human food purchase respectively, Table 4). All in
523 all, this system provides an additional +58.7 kgN ha⁻¹ year⁻¹ of inputs at village *terroir* level,
524 which is a major advantage, because the soils in sub-Saharan Africa are poor in nutrients and
525 most systems are soil mining systems.

526 In both Diohine and Barry villages, gross margin yields are negative (§ 3.3.5), leading to the
527 assumption that some household expenditures are covered by off-farm activities, as reported in
528 other studies conducted by the Niakhar observatory (Maffray, 2014; Reiff and Gros, 2004).
529 Nevertheless, agricultural income (AI) is 24% higher in Barry. Higher incomes and higher meat
530 and crop yields make it possible to maintain a 78% higher population density in Barry than in
531 Diohine (§ 3.1.2). These results confirm the hypothesis proposed by Duncan et al. (2013):
532 livestock fattening-based systems could be way to reduce rural exodus.

533 Semi-intensive livestock production (fattening or off-season milk production) has
534 already been identified as a relevant option to offset declining cash crop markets in a range of
535 different contexts in sub-Saharan Africa (e.g. Mali, Burkina Faso, Madagascar) (de Ridder et
536 al., 2015). In the groundnut basin in Senegal, the incentives for groundnut cultivation declined
537 drastically in the 1970s leading to the rapid reduction in the cultivation of this cash crop and in
538 the use of mineral fertilizers (Lericollais, 1999). Livestock fattening favors the cultivation of
539 cash crops, since the economic gains from livestock rearing are partially invested in inputs like
540 seeds and fertilizers (§ 3.1.2). In the present study, the livestock fattening system appears to be
541 a promising option for agricultural intensification. The expected increase in the demand for
542 meat and milk in sub-Saharan Africa represents an opportunity to increase the attractiveness
543 and sustainability of rural areas if livestock intensification is developed.

544 **4.3. Better manure management practices would increase the benefits of higher nutrient** 545 **inputs in the semi-intensive system**

546 This study confirmed that solid manure is a key resource for the sustainable
547 intensification of agricultural systems in sub-Saharan Africa (Rufino et al., 2011) as the use of
548 mineral fertilizers is still limited in the Senegalese villages studied here (1.09 kgN ha⁻¹ in
549 Diohine and 6.28 kgN ha⁻¹ in Barry). Section 3.3.3 underlined gaps in the nitrogen balance
550 depending on the level of analysis (§ 3.3.3). Indeed, the nitrogen balance is generally negative
551 at plot level and positive at household and village *terroir* levels. This result is consistent with
552 those of other studies in sub-Saharan Africa (Diarisso et al., 2015). Our in-depth analysis of N
553 flows in farming systems (at the household level) in the two study village *terroirs* explains these

554 differences in the nitrogen balance by inefficient use of organic fertilizers produced by
555 livestock: urine and solid manure. In both villages, some of the N produced on-farm
556 accumulates in the holdings and is not applied to the plots. Differences between N balances at
557 plot and village *terroir* levels are even bigger in Barry (§ 3.3.3) where solid manure recycling
558 is less efficient. Our analysis of N flows at household level indicates that recycling of solid
559 manure depends to a great extent on the type of household (§ 3.1.3). Paradoxically, the more
560 solid manure that is available, the less is applied per TLU. What is more, the efficient use of
561 solid manure depends to a great extent on the orientation of the household's farming activities.
562 For instance, in Barry, households that focus on the livestock trade (the HRE-LH, type 5), do
563 not pay much attention to cropping and nor efficiently recycle solid manure, as they use the
564 income they obtain by fattening livestock to buy a large part of their human food. In contrast,
565 households that focus on both trading livestock and growing cash crops such as MRE-MH, type
566 3, recycle solid manure more efficiently. These results are consistent with those of other studies
567 conducted in sub-Saharan Africa (Dugue, 1998; Rufino et al., 2009; Schlecht et al., 2006).

568 The transition from the extensive system, (i.e., that used in Diohine village) where
569 excreta is directly deposited on fields by livestock, to the semi-intensive system (i.e., that used
570 in Barry village) where solid manure is collected, stored, matured and spread on the fields by
571 humans, calls for new knowledge and means of production to enable more efficient use of solid
572 manure. Indeed, opportunities to improve crop-livestock integration and soil fertility were
573 identified with local stakeholders during participatory workshops (Audouin et al., 2018).
574 Audouin (2015), the environmental, technical and economic impacts of the most promising
575 option were evaluated for both villages: improvement of solid manure recycling by increasing
576 solid manure transport capacity (i.e. more horse drawn carts) and the creation of manure pits
577 like those experimented in Burkina Faso (Blanchard et al., 2011).

578 *Appendix 8*

579 This evaluation revealed more opportunities for improvement in households with higher
580 livestock stocking rates and where livestock-fattening activities predominate (Appendix 8).

581 **4.4. Use of feed concentrate increases system dependency but also improves its resilience** 582 **in the face of local climate variability**

583 However, livestock fattening-based systems still require large amounts of imported feed to
584 maintain a high livestock stocking rate (2.31 UBT ha⁻¹). All the farmers in Barry import a total
585 of 411 * 10³ kgDM of feed concentrate annually (§ 3.3.2.) thereby increasing the dependence
586 of village *terroir* on external inputs, which is 6.7 times higher in Barry than in Diohine.

587 The use of feed concentrate is questionable. While it reduces household autonomy and
588 exposes the households to fluctuations in the price of cereals and industrial by-products, it also
589 reduces the pressure created by the production system on local natural resources (e.g. soil and
590 trees) and renders them less sensitive to local climate hazard (Grillot et al., 2018b). Indeed, in
591 a traditional system (such as Diohine) the wooded parkland is subject to high pressure to feed
592 livestock in dry years to counterbalance the shortage of crop residues (§ 3.2.1.). The
593 sustainability of traditional systems is thus called into question during long periods of drought.
594 This was the case during the droughts in the 1970s and 1980s that led to the decline of
595 *Faidherbia albida* parklands (Ndiaye et al., 2016). In a livestock fattening-based system (such
596 as that in Barry), the lack of fodder in dry years has less impact since feed concentrates account
597 for most of livestock's feed ration. In a context of rapid climate change and marked climate
598 uncertainty (Roudier et al., 2011) as well as ongoing land saturation (Dongmo et al., 2012),
599 livestock fattening is attractive because the animals are kept in barns and stall-fed using feed
600 resources most of which are imported from outside the villages.

601

602 **5. Conclusion**

603 This article reports the results of comparative analysis of two existing village *terroirs* that
604 use contrasted agricultural systems based on different livestock activities. The system used in
605 the village of Diohine is close to the *Serer's* traditional agro-sylvo-pastoral system organized
606 around grazing livestock and common fallow. The system used in the second village, Barry, is
607 organized around stall-fed livestock fattening.

608 Diohine is an old village *terroir* where the intergenerational social hierarchy plays a
609 predominant role in the collective management of local resources. Rangelands and common
610 fallow play a key role in supporting the mobile livestock that drive biomass and nutrient
611 transfers in the landscape. But limited extent of rangelands result in insufficient nutrient
612 transfers from rangelands to croplands that no longer compensate for the export of nutrients in
613 the form of grains and residues from crop fields. This calls the sustainability of this traditional
614 system into question.

615 Barry village *terroir* is more recent. It has evolved toward a more individual and intensive
616 resource management system, in which the use of feed concentrate and mineral fertilizer plays
617 an important role. Feed concentrate for livestock fattening represent a major household N
618 inflow. The livestock fattening system enables higher sustainability in terms of productivity,
619 profitability, and soil fertility (i.e. the nitrogen balance). Indeed, this systems enables a higher
620 livestock stocking rate, which, in turn, makes organic matter more available, leading to higher

621 crop and livestock N productivity (+39 % for crop main products, +45 % for crop by-products,
622 +720% for meat). Additional cash flows (+24%) make it possible to increase crop and
623 household inputs (mineral fertilizers and human food) resulting in a 2.93 times higher village
624 *terroir* N balance and a 78% higher population density.

625 This study reinforces the hypothesis that livestock fattening is a promising pathway for the
626 sustainable intensification of agricultural systems in rural areas in sub-Saharan Africa, and
627 hence to reduce rural exodus. However, the increased quantities of solid manure that would
628 then become available need be used more efficiently, by increasing its return and its benefits to
629 crops, and by reinforcing crop-livestock integration. The main limitation of the system based
630 on livestock fattening is that imports of feed concentrates increase the dependency of
631 households and villages on external inputs and hence their sensitivity to fluctuating market
632 prices; on the other hand, livestock fattening reduces the pressure on local natural resources and
633 reduces sensitivity to local climate variability.

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845 **Appendices**

846 Appendix 1: Conversion factors from local to standard units

Category	Indicator	Unit	Value	Origin or reference
<i>Seeds</i>				
	bag of cabbage seeds	kgFM	0.3	survey
	bag of chili seeds	kgFM	0.3	survey
	bag of eggplant seeds	kgFM	0.3	survey
	bag of tomato seeds	kgFM	0.3	survey
	basin of bissap seeds (<i>Hibiscus sabdariffa</i>)	kgFM	6.0	estimated
	basin of groundnut seeds	kgFM	30.0	survey
	cup of onion seeds	kg FM	0.1	survey
	handful of bissap	kgFM	0.1	calculated
	handful of cowpea	kgFM	0.2	calculated
	handful of groundnut	kgFM	0.2	calculated
	handful of okra	kgFM	0.1	survey
	heap of cassava seeds	kgFM	0.5	survey
	pot of onion seeds	kgFM	0.1	survey
	seed drill of groundnut	kgFM	5.0	survey
	seed drill of sorghum	kgFM	2.0	survey
	1L of bissap seeds	kgFM	0.9	weighed
	1.5L bottle of cowpea seeds	kgFM	1.5	weighed
	10L container of sorghum grains	kgFM	10.0	survey
	20L container of cowpea seeds	kgFM	20.0	weighed
	1kg tomato pot of bissap seeds	kgFM	0.9	weighed
	1kg pineapple pot of bissap seeds	kgFM	0.4	weighed
	50kg bag of groundnut seeds	kgFM	55.0	survey
<i>Organic matter</i>				
	basin of solid manure	kgFM	5.6	survey
	basin of leftover feed	kgFM	17.0	estimated
	basin of waste	kgFM	7.0	weighed
	bucket of waste	kgFM	3.5	weighed
	horse cart of solid manure	kgFM	280.0	survey
	donkey cart of solid manure	kgFM	186.7	survey
	cart of leftover feed	kgFM	180.0	estimated
	cart of solid manure free of leftover feed	kgFM	315.0	calculated

wheelbarrow of solid manure	kgFM	22.8	calculated
wheelbarrow of solid manure with straw	kgFM	20.3	calculated
50kg bag of fresh solid manure	kgFM	30.0	weighed
50kg bag of poultry manure	kgFM	40.0	survey

Mineral fertilizers

bag of millet fertilizer	kgFM	50.0	literature
bag of 10-20-20 fertilizer	kgFM	50.0	literature
handful of "millet fertilizer"	kgFM	0.2	estimated
pot of fertilizer	kgFM	1.0	estimated

By-products

basin of fresh cowpea hay	kgFM	20.0	literature
basin of groundnut hay	kgFM	4.3	calculated
horse cart of cowpea hay	kgFM	238.0	survey
horse cart of millet straw	kgFM	210	literature
horse cart of sorghum straw	kgFM	210	survey
donkey cart of cowpea hay	kgFM	158.667	survey
donkey cart of millet straw	kgFM	140	survey
donkey cart of sorghum straw	kgFM	140	survey
cart of corn straw	kgFM	224.0	calculated
cart of cowpea hay	kgFM	238.0	calculated
cart of groundnut hay	kgFM	238.0	calculated
cart of millet straw	kgFM	210.0	calculated
cart of sorghum straw	kgFM	210.0	calculated
cart of watermelon straw	kgFM	200.0	estimated
bundle of corn	kgFM	20.0	estimated
bundle of millet	kgFM	11.0	weighed
bundle of millet stalks	kgFM	7.5	weighed
bundle of sorghum	kgFM	11.0	weighed
heap of groundnut hay	kgFM	8.0	survey
50kg bag of fresh cowpea hay	kgFM	25.0	estimated
100kg bag of cowpea hay	kgFM	17.0	weighed on Mbfaye market
100kg bag of groundnut hay	kgFM	17.0	weighed on Mbfaye market

Main crops

barigot ¹ of corn	kgFM	85.0	weighed on Mbafaye market
barigot ¹ of cowpea	kgFM	135.0	literature
barigot ¹ of groundnut	kgFM	100.0	estimated
barigot ¹ of millet	kgFM	100.0	estimated
barigot ¹ of sorghum	kgFM	110.0	estimated
basin of bissap	kgFM	4.3	weighed on Mbafaye market
basin of dried cowpea	kgFM	30.0	literature; survey
basin of fresh cowpea	kgFM	5.0	survey
basin of black eggplants	kgFM	20.0	survey
basin of green eggplants	kgFM	25.0	survey
basin of unhusked groundnut	kgFM	15.0	literature
basin of matye millet grain	kgFM	14.4	survey
basin of pod millet grain	kgFM	12.0	survey
basin of onions	kgFM	25.0	survey
basin of sorghum grain	kgFM	10.0	weighed
basin of tomatoes	kgFM	37.5	survey
bowl of okra	kgFM	1.0	survey
bucket of cabbage	kgFM	10.0	survey
bucket of chili	kgFM	5.0	survey
bucket of dried cowpea	kgFM	15.0	survey
bucket of fresh cowpea	kgFM	2.5	survey
bucket of eggplant	kgFM	10.0	survey
horse cart of millet ears	kgFM	276.0	literature; survey
horse cart of sorghum branches	kgFM	150.0	literature
donkey cart of millet ears	kgFM	184.0	survey
donkey cart of sorghum branches	kgFM	100.0	calculated
cart of matye millet	kgFM	331.2	survey
cart of sorghum ear	kgFM	150.0	literature
pineapple pot of bissap	kgFM	0.425	weighed
pot of tomatoes	kgFM	1.5	survey
sheaf of matye millet	kgFM	14.4	survey
sheaf of pod millet	kgFM	12.0	literature; survey
10L bottle of dried cowpeas	kgFM	10.0	survey

¹ barrel

50kg bag of bissap	kgFM	6.4 weighed
50kg bag of cabbage	kgFM	40.0 survey
50kg bag of chili	kgFM	17.0 survey
50kg bag of corn grain	kgFM	42.5 weighed on Mbafaye market
50kg bag of black eggplant	kgFM	21.5 survey
50kg bag of millet grains	kgFM	50.0 survey
50kg bag of onions	kgFM	30.0 survey
50kg bag of sorghum branches	kgFM	12.5 literature
50kg bag of crushed sorghum	kgFM	55.0 survey
50kg bag of sorghum grain	kgFM	55.0 weighed on Mbafaye market
100kg bag of unhusked cowpea	kgFM	67.5 literature
100kg bag of husked groundnut	kgFM	80.0 survey
100kg bag of unhusked groundnut	kgFM	60.0 literature
100kg bag of uncrushed sorghum	kgFM	80.0 survey

Concentrates

basin of millet ears	kgFM	4.0 weighed
basin of rice bran	kgFM	8.5 calculated
disc of groundnut cake	kgFM	2.2 weighed
handful of chick feed	kgFM	0.2 estimated
handful of concentrates	kgFM	0.2 estimated
handful of groundnut cake	kgFM	0.2 estimated
handful of millet bran	kgFM	0.2 survey
handful of millet	kgFM	0.2 estimated
handful of rice bran	kgFM	0.2 estimated
pot of concentrate	kgFM	1.6 weighed on Mbafaye market
pot of cotton grain	kgFM	1.0 calculated
pot of cowpeas	kgFM	1.4 calculated
pot of groundnut cake	kgFM	0.7 weighed on Mbafaye market
pot of millet bran	kgFM	1.0 weighed on Mbafaye market
pot of millet grain	kgFM	1.0 estimated

pot of rice bran	kgFM	0.9	weighed on Mbafaye market
pot of sorghum grain	kgFM	1.1	estimated
2.5kg tomato pot of millet bran	kgFM	1.0	weighed
100kg bag of rice bran	kgFM	85.0	calculated
100kg bag of millet bran	kgFM	100.0	weighed on Mbafaye market
100kg bag of cotton grain	kgFM	100.0	survey
100kg bag of <i>Faidherbia albida</i> fruits	kgFM	20.0	estimated

Fodder

bag of millet bran	kgFM	50.0	literature
bag of rice bran	kgFM	50.0	literature
basin of cowpea hay	kgFM	4.3	calculated
basin of corn straw	kgFM	5.3	calculated
basin of millet straw	kgFM	5.0	survey
basin of sorghum straw	kgFM	5.0	estimated
basin of weeds	kgFM	4.8	calculated
leaves of a branch of <i>Faidherbia albida</i>	kgFM	10.0	survey
bundle of corn straw	kgFM	10.0	literature
bundle of cowpea hay	kgFM	6.7	calculated
bundle of groundnut hay	kgFM	8.5	calculated
bundle of millet	kgFM	10.0	weighed
bundle of sorghum	kgFM	11.0	weighed
handful of groundnut hay	kgFM	0.2	calculated
wheelbarrow of dried weeds	kgFM	5.0	survey
50kg bag of weeds	kgFM	16.0	survey
100kg bag of weeds	kgFM	32.0	weighed
100kg bag of cowpea hay	kgFM	14.0	weighed
100kg bag of groundnut hay	kgFM	17.0	weighed

Household food supplies

dried fish	kg FCFA ⁻¹	0.0026	weighed on Mbafaye market
heap of meat	kgFM	0.5	survey
handful of rice	kgFM	0.1	weighed
pot of corn	kgFM	0.9	weighed on Mbafaye market

Plate of groundnut cake	kgFM	2.2 weighed on Mbafaye market
Household waste		
basin of waste	kgFM	7.0 weighed
Wood		
cart of wood	kgFM	420.4 literature
bundle of wood	kgFM	14.8 weighed Barry Sine
Building		
sheaf of branches for fencing (free of leaves)	kgFM	7.5 weighed

847

848 Appendix 2: Consumption of crop residues, table of coefficients

Indicator	Unit	Value	Origin or reference
Common grazing withdrawal	kgDM TLU ⁻¹ day ⁻¹	4.75	Diop et al.. 2005
Withdrawal portion of millet straw	%DM	0.33	Dongmo et al.. 2009
Withdrawal portion of sorghum straw	%DM	0.33	Dongmo et al. 2009
Withdrawal portion of corn stalks	%DM	0.67	Dongmo et al. 2009
Withdrawal portion of groundnut hay	%DM	0	field observation
Withdrawal portion of cowpea hay	%DM	0	field observation
Withdrawal portion of watermelon straw	%DM	0	field observation

849

850 Appendix 3: Deposition rates during grazing by the herd

Indicator	Unit	Value	Reference
<i>Feces deposited</i>			
Wet season	kgDM day ⁻¹ TLU ⁻¹	3.4	Wade et al., 2016
Cool dry season	kgDM day ⁻¹ TLU ⁻¹	2.1	Wade et al., 2016
Hot dry season	kgDM day ⁻¹ TLU ⁻¹	3.0	Wade et al., 2016
<i>Urine</i>	kgFM day ⁻¹ TLU ⁻¹	3	Dongmo et al., 2009

851

852 Appendix 4: Feces nitrogen content kgN kgDM⁻¹ according to the season (Source: Manlay. 2001)

Month	Nitrogen content kgN kgDM⁻¹
Wet season	0.0182
Cool dry season	0.0168
Hot dry season	0.0148

853

Indicator	Dry matter conversion factor kgDM kgFM⁻¹	Origin or reference	Nitrogen conversion factor kgN kgDM⁻¹	Origin or reference
Corn grain	0.912	Le Thiec. 1996	0.01664	Le Thiec 1996
Millet grain	0.91	Wade 2016	0.01920	Le Thiec 1996
Sorghum grain	0.910	Le Thiec 1996	0.0184	Wade 2016
Groundnut grain	0.860	Le Thiec 1996	0.06224	Le Thiec 1996
Watermelon grain	0.089	estimated	0.00096	estimated
Cowpea grain	0.892	Maliboungou et al.. 1998	0.04466	Maliboungou et al. 1998
Bissap grain	1.000	USDA Nutirent Laboratory. 2013	0.00100	USDA Nutrient Laboratory 2013
Groundnut hay	0.896	Le Thiec 1996	0.01700	(Manlay. 2001)
Millet straw	0.88	Wade 2016	0.0055	Wade 2016
Sorghum straw	0.896	Le Thiec 1996	0.00544	Le Thiec 1996
Cowpea hay	0.902	Le Thiec 1996	0.02395	Le Thiec 1996
Watermelon stalk	0.089	estimated	0.00096	estimated
Corn stalk	0.895	Le Thiec 1996	0.00800	Manlay 2001
Corn cob	0.650	Alvarez et al.. 2013	0.01210	Manlay 2001
Millet bale	0.989	Manlay 2001	0.01230	Manlay 2001
Sorghum bale	0.998	Manlay 2001	0.01600	Manlay 2001
Groundnut pod	0.865	Le Thiec 1996	0.02870	Manlay 2001

Watermelon	0.089	ANSES 2012	0.00096	ANSES 2012
Bissap flower	0.405	Courtial et al., 1998	0.02410	Courtial et al. 1998
Rice	0.870	Alvarez et al. 2013	0.01500	Alvarez et al. 2013
Meat	0.800	Huss. 1999	0.25000	Huss 1999
Fish	0.265	Huss 1999	0.11169	Huss 1999
Compact manure	0.320	Alvarez et al. 2013	0.01600	Alvarez et al. 2013
Manure containing straw	0.450	Ganry and Badiane. 1998	0.00500	Ganry and Badiane 1998
Sewage powder	0.450	Ganry and Badiane 1998	0.00440	Ganry and Badiane 1998
Animal feed residues	0.881	Le Thiec 1996	0.00270	Le Thiec 1996
Household waste	0.500	Alvarez et al. 2013	0.00600	Alvarez et al. 2013
Wood	0.880	Loupe. 2012	0.00300	Loupe 2012
Fresh pasture	0.45	Wade 2016	0.0174	Wade 2016
<i>Faidherbia albida</i> leaves	0.307	Wentling. 1983	0.01552	Fall. 1989
Dry pasture	0.68	Wade 2016	0.0090	Wade 2016
Fresh cowpea hay	0.203	Le Thiec 1996	0.02434	Le Thiec 1996
Baobab leaves	0.896	Abakar. 2010	0.00900	Abakar 2010
Cotton grain	0.930	Le Thiec 1996	0.03072	Le Thiec 1996
Groundnut cake	0.95	Wade 2016	0.0702	Wade 2016
Rice bran	0.95	Wade 2016	0.0092	Wade 2016
Millet bran	0.95	Wade	0.0297	Wade 2016

Feed concentrate	0.89	-Wade 2016	0.0232	Wade 2016
<i>Acacia albida</i> fruits	0.900	Fall-Touré et al. 1997	0.11220	Richard et al.. 1990
Milk	-	-	0.005 (/kgFM)	Rufino et al. 2009
Urea	1	field observation	0.46	field observation
« Millet mineral fertilizer »	1	field observation	0.15	field observation
« Groundnut mineral fertilizer»	1	field observation	0.10	field observation
Urine	0.075	Audoin. 1991	0.000675	Audoin 1991

855

Category	Indicator	Unit	Purchase price	Sale price	Origin
Biomass					
Mineral fertilizers					
	Urea	€ kgFM ⁻¹	0.24	-	calculated
	Millet mineral fertilizer	€ kgFM ⁻¹	0.22	-	calculated
	Groundnut mineral fertilizer	€ kgFM ⁻¹	0.21	-	calculated
Organic fertilizers					
	Poultry manure	€ kgFM ⁻¹	0.12	-	estimated
Pesticides					
	Seed insecticide	€ pill ⁻¹	0.17	-	calculated
Main plant production					
	Corn	€ kgFM ⁻¹	0.33	0.39	calculated/estimated
	Millet	€ kgFM ⁻¹	0.33	0.30	estimated/calculated
	Millet bundle	€ kgFM ⁻¹	0.18	0.18	estimated
	Sorghum	€ kgFM ⁻¹	0.49	0.34	calculated
	Sorghum bundle	€ kgFM ⁻¹		0.29	calculated
	Groundnut	€ kgFM ⁻¹	1.18	0.41	calculated
	Shell-on groundnut	€ kgFM ⁻¹		0.45	calculated
	Watermelon seed	€ kgFM ⁻¹	18.24		calculated
	Watermelon	€ kgFM ⁻¹		1.29	calculated
	Cowpea	€ kgFM ⁻¹	0.80	0.48	calculated
	Bissap seeds (<i>Hibiscus sabdariffa</i>)	€ kgFM ⁻¹	0.33	-	estimated
	Bissap (<i>Hibiscus sabdariffa</i>)	€ kgFM ⁻¹	-	1.65	calculated
	Onion seeds	€ kgFM ⁻¹	18.24		estimated
	Onion	€ kgFM ⁻¹	-	0.61	estimated
	Chili pepper seed	€ kgFM ⁻¹	18.24	-	estimated
	Chili pepper	€ kgFM ⁻¹	-	1.29	estimated
	Tomato seed	€ kgFM ⁻¹	18.24	-	estimated
	Tomato	€ kgFM ⁻¹	-	0.51	estimated
	Cassava seed	€ kgFM ⁻¹	18.24	-	estimated
	Green eggplant seed	€ kgFM ⁻¹	18.24	-	estimated

Green eggplant	€ kgFM ⁻¹	-	1.29	estimated
Black eggplant seed	€ kgFM ⁻¹	18.24	-	estimated
Black eggplant	€ kgFM ⁻¹	-	1.29	estimated
Head cabbage seed	€ kgFM ⁻¹	18.24	-	estimated
Head cabbage	€ kg FM ⁻¹	-	0.46	estimated
Okra	€ kgFM ⁻¹	18.24	-	estimated
<i>Fodder</i>				
Groundnut hay	€ kgFM ⁻¹	0.37	0.16	calculated
Millet straw	€ kgFM ⁻¹	0.03	0.03	calculated
Sorghum straw	€ kgFM ⁻¹	-	0.03	estimated
Cowpea hay	€ kgFM ⁻¹	0.81	0.81	calculated/estimated
<i>Concentrates</i>				
"Livestock feed"	€ kgFM ⁻¹	0.21	-	calculated
Rice bran	€ kgFM ⁻¹	0.16	-	calculated
Millet bran	€ kgFM ⁻¹	0.14	-	calculated
Groundnut cake	€ kgFM ⁻¹	0.30	-	estimated
Cotton grain	€ kgFM ⁻¹	0.17	-	estimated
Wheat bran	€ kgFM ⁻¹	0.15	-	estimated
Groundnut cuticle	€ kgFM ⁻¹	0.08	-	estimated
<i>Human food</i>				
Rice	€ kgFM ⁻¹	0.45	-	calculated
Cowpea	€ kgFM ⁻¹	0.76	-	calculated
Groundnut	€ kgFM ⁻¹	1.10	-	calculated
Meat	€ kgFM ⁻¹	2.88	-	calculated
Fish	€ kgFM ⁻¹	0.58	-	calculated
Oil	€ L ⁻¹	1.49	-	calculated
Sugar	€ kgFM ⁻¹	0.90	-	calculated
Groundnut cake	€ plate ⁻¹	1.75	-	calculated
Bread	€ unit ⁻¹	0.17	-	calculated
<i>Fuel</i>				
Wood	€ kgFM ⁻¹	0.02	0.02	calculated/estimated
Coal	€ kgFM ⁻¹	0.25	-	calculated
Gas	€ unit ⁻¹	5.89	-	calculated
<i>Animal</i>				
Male calf <6 months	€ unit ⁻¹	237.50	126.67	calculated
Male calf 6-12 months	€ unit ⁻¹	116.53	197.60	calculated/estimated

Male bull 1-2 years	€ unit ⁻¹	161.29	268.53	calculated
Male bull 2-3 years	€ unit ⁻¹	214.49	360.24	calculated
Male bull >3 years	€ unit ⁻¹	300.60	505.96	calculated
Female calf <6 months	€ unit ⁻¹	38.84	84.44	estimated
Female calf 6-12 months	€ unit ⁻¹	77.69	131.73	estimated
Female heifer 1-2 years	€ unit ⁻¹	107.53	361.00	estimated/calculated
Female heifer 2-3 years	€ unit ⁻¹	129.20	400.27	calculated/estimated
Female heifer >3 years	€ unit ⁻¹	291.35	439.53	calculated
Lamb	€ unit ⁻¹	29.69	73.23	calculated
Mature sheep	€ unit ⁻¹	62.06	118.36	calculated
Kid	€ unit ⁻¹	22.71	18.75	calculated
Mature goat	€ unit ⁻¹	26.25	30.80	calculated
Chick	€ unit ⁻¹	0.02	0.02	estimated
Chicken	€ unit ⁻¹	2.48	2.84	calculated
Foal	€ unit ⁻¹	286.90	286.90	calculated/estimated
Mature horse	€ unit ⁻¹	239.89	273.60	calculated
Young donkey	€ unit ⁻¹	60.80	60.80	calculated/estimated
Mature donkey	€ unit ⁻¹	49.40	22.80	calculated
Duckling	€ unit ⁻¹	0.04	0.04	estimated
Mature duck	€ unit ⁻¹	3.72	5.58	estimated
Turkey chick	€ unit ⁻¹	0.12	0.12	estimated
Turkey	€ unit ⁻¹	7.60	11.40	calculated/estimated
Piglet	€ unit ⁻¹	9.12	13.68	estimated
Mature pig	€ unit ⁻¹	30.40	45.60	estimated

857

Farm equipment	Unit	Cost	Origin
<i>Depreciation</i>			
Horse	€ year ⁻¹	15.20	Reiff and Gros. 2004
Donkey	€ year ⁻¹	1.52	Reiff and Gros. 2004
Cart	€ year ⁻¹	6.08	Reiff and Gros. 2004
Seeder	€ year ⁻¹	2.28	Reiff and Gros. 2004
"Western hoe"	€ year ⁻¹	1.26	Reiff and Gros. 2004
"Sine hoe"	€ year ⁻¹	0.76	Reiff and Gros. 2004
<i>Maintenance</i>			
Cart	€ year ⁻¹	11.40	Reiff and Gros. 2004
Seeder	€ year ⁻¹	3.04	Reiff and Gros. 2004
"Western hoe"	€ year ⁻¹	2.28	Reiff and Gros. 2004
"Sine hoe"	€ year ⁻¹	2.28	Reiff and Gros. 2004
"Iler"	€ year ⁻¹	0.46	Reiff and Gros. 2004

860 Appendix 8. Environmental, technical and economic gains obtained by digging manure pits per
 861 household and per year (Audouin, 2014).

Household type	Number of 9 m ³ manure pits required	Manure kgDM ha ⁻¹	Millet grains kgDM ha ⁻¹	Economic gain (AI)* €	N balance/plot kgN ha ⁻¹
1- LRE- SH	2	+155	+21	+30	+3.1
2- MRE-SH	2	+58	+9	+17	+1.9
3- MRE-MH	5	+231	+34	+45	+5.8
4- HRE-MH	2	+20	+6	+8	+2.4
5- HRE-LH	8	+357	+142	+327	+4.3
Diohine average	2	+24	+3	+1	+1.8
Barry Sine average	4	+161	+30	+64	+3.3

862 * hypothesis: all surplus grain is sold.

863

864 **Tables**

865 Table 1. Main features of the five types of household in Diohine and Barry

Number given to type		1	2	3	4	5
Code name of type		LRE-SH	MRE-SH	MRE-MH	HRE-MH	HRE-LH
Livestock stocking rate	TLU ha-1	1.3	1.3	3.1	3.6	3.7
Importance of livestock fattening	% of total TLU	23	15	32	03	59
Population density	capita ha-1	4.5	2.8	4.2	3.1	6.3
Total cultivated area	ha	3.8	5.5	5.2	5.3	4.9
Importance of groundnut	% of TCA	26	19	32	8	20
Importance of fallow	% of TCA	2	11	2	19	0
Free-grazing plant biomass balance (Δ FG)	kgDM ha-1 year-1	-225	-61	-2	3451	-566
Manure inputs during night corralling	kgDM ha-1 year-1	113	25	218	758	323
Free-grazing and night corralling balance	kgN ha-1 year-1	0.15	2.99	8.43	3.69	9.93
Availability of solid manure from livestock housed in barns	TLU.h	24843	19431	49274	12505	95522
Solid manure input rate per livestock tethered close to the homestead	kgN TLU.h-1	0.00030	0.00063	0.00040	0.00055	0.00012
Nitrogen balance at household level	kgN ha-1 year-1	52.6	-0.2	42.4	43.0	151.0
Percentage of household in Diohine	%	11	78	0	11	0
Percentage of household in Barry	%	26	49	19	0	6

866

867

868 Table 2. Main indicators of crop fertilization at plot level, average results for the total cultivated area
 869 (TCA) in Diohine and Barry for the 2012-2013 cropping season

Indicator	Units	Diohine	Barry
<i>Herd-driven deposition of excreta during free grazing</i>			
Rate of deposition during free grazing	% IN	46	25
Balance of flows driven by free-grazing livestock-in the wet season	kgN ha ⁻¹	-8.32	-26
Balance of flows driven by free-grazing livestock-in the dry season	kgN ha ⁻¹	0.55	5.04
<i>Herd-driven deposition during night corralling</i>			
Input rate during night corralling in the wet and dry season	% IN	15	15
Night corralling area in the wet season	% TCA	2.7	0.2
Deposition of excreta during night corralling in the wet season	kgDM ha ⁻¹	83	20
Night corralling area in the dry season	% TCA	3	39
Deposition of excreta during night corralling in the dry season	kgDM ha ⁻¹	51	204
<i>Human application of solid manure</i>			
Inputs of solid manure as a percentage of total inputs	% IN	14	12
Area of application of solid manure	% TCA	22	31
Volume of manure applied	kgDM ha ⁻¹	337	482
<i>Human application of mineral fertilizer</i>			
Inputs of mineral fertilizer as a percentage of total inputs	% IN	8	27
Area of application of mineral fertilizer	% TCA	2	27
Volume of mineral fertilizer applied	kgN ha ⁻¹	1.09	6.28
<i>Human application of waste</i>			
Waste inputs as a percentage of total inputs	% IN	14	16
Area of application of waste	% TCA		
Volume of waste applied	kgN ha ⁻¹	1.86	3.75
<i>Human application of seeds</i>			
Seeds input as a percentage of total inputs	% IN	3	6
Area of application of seeds	% TCA	100	100
Volume of seeds applied	kgN ha ⁻¹	0.47	1.30

870

871 Table 3. Yields of main crop -products and by-products at plot level; Proportion of by-products left on
 872 the ground for the 2012-2013 cropping season in Diohine and Barry.

Indicator	Units	Diohine	Barry
<i>Yields of main products</i>			
Millet ear	kgDM ha ⁻¹	626	727
Sorghum ear	kgDM ha ⁻¹	480	779
Groundnut pod	kgDM ha ⁻¹	371	366
<i>Byproducts yields</i>			
Millet straw	kgDM ha ⁻¹	1 823	2 418
Sorghum straw	kgDM ha ⁻¹	1 067	2 505
Groundnut hay	kgDM ha ⁻¹	1 171	696
<i>Proportion of by-products left on the grounds</i>			
Millet	%	60	43
Sorghum	%	44	13
Groundnut	%	31	0

873

874

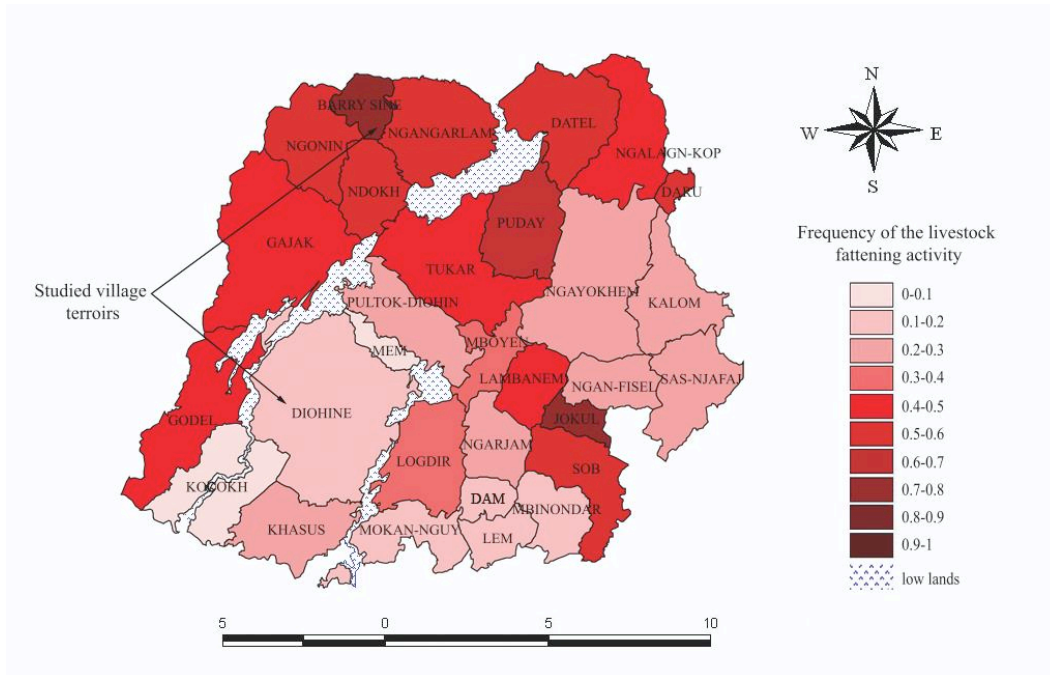
875 Table 4. N flows entering, leaving, and circulating within village *terroirs* and corresponding N-flow-
 876 based indicators at village *terroir* level for Diohine and Barry for the 2012-2013 cropping season

	Units	Diohine	Barry
<i>Input flows</i>			
Human food	kgN ha ⁻¹	3.73	4.85
Seeds	kgN ha ⁻¹	0.21	0.38
Mineral fertilizers	kgN ha ⁻¹	0.92	5.16
Direct withdrawal biomass ²	kgN ha ⁻¹	0.74	0.88
Livestock	kgN ha ⁻¹	0.60	33.51
Fodder	kgN ha ⁻¹	0.22	0.37
Feed concentrates	kgN ha ⁻¹	3.39	23.67
<i>Output flows</i>			
Main crop products	kgN ha ⁻¹	0.11	0.88
Crop by-products	kgN ha ⁻¹	0.02	0.12
Livestock	kgN ha ⁻¹	1.00	42.48
Milk	kgN ha ⁻¹	0.00	0.37
Manure and urine	kgN ha ⁻¹	0.31	0.10
<i>Summary of flows</i>			
Total inputs (IN)	kgN ha ⁻¹	10.06	68.82
Total outputs (ON)	kgN ha ⁻¹	1.55	43.95
Total system throughflow (TST)	kgN ha ⁻¹	14.14	18.02
Dependence (D=IN/TST)	dmnl	2.03	12.66
SSFeed	%	86	70
SSFert	%	96	67
N balance (NB)	kg ha ⁻¹	8.51	24.88
N use efficiency (NUE)	dmnl	0.15	0.64

877

² Free grazing of plant biomass outside the boundaries of the village

878 **Figures**

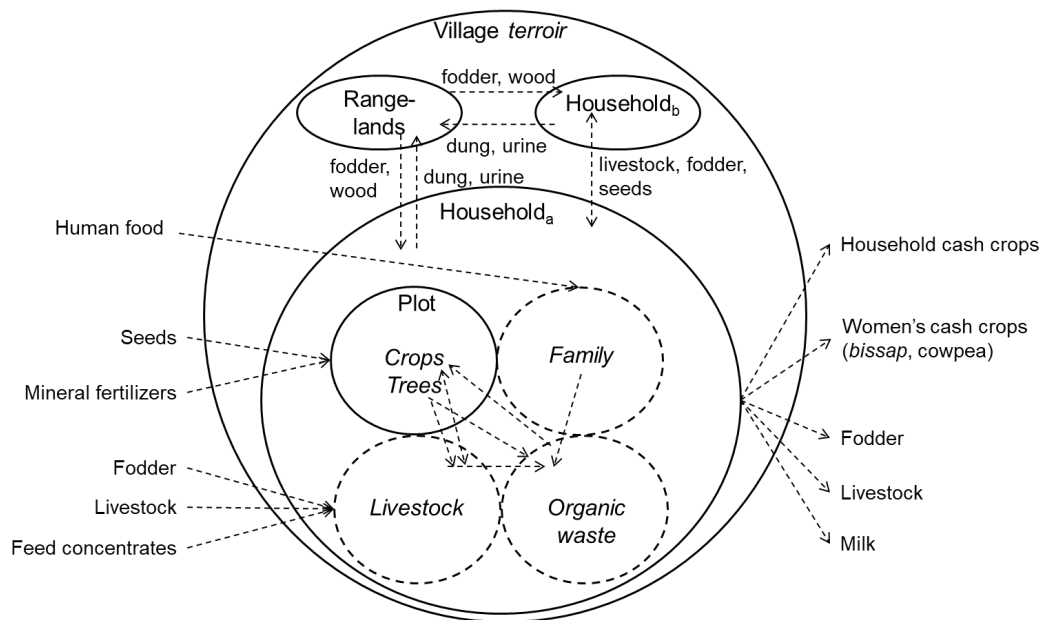


879

880 Figure 1. Portion of holdings that practice livestock fattening in 2012 in the 30 village *terroirs* of the
 881 Niakhar demographic and health observatory (Delaunay et Lalou, 2012).

882 *2 columns, color*

883

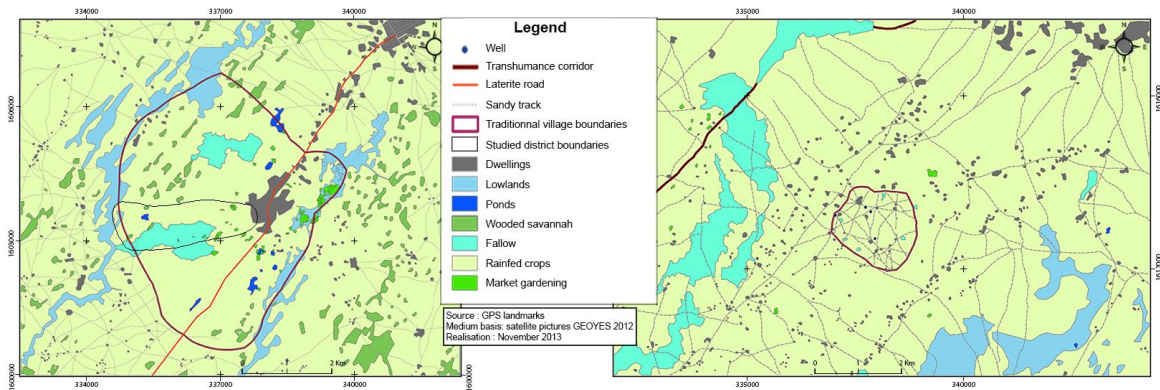


884

885 Figure 2. Conceptual stock-flow model of the system studied with three interlocking systems: plot,
 886 household and village *terroir*

887 *1.5 columns*

888



889

890 Figure 3. Agro-ecological zoning of Diohine (left) and Barry (right) during the 2012-2013 cropping
891 season.

892 *2 columns, color*

893

894

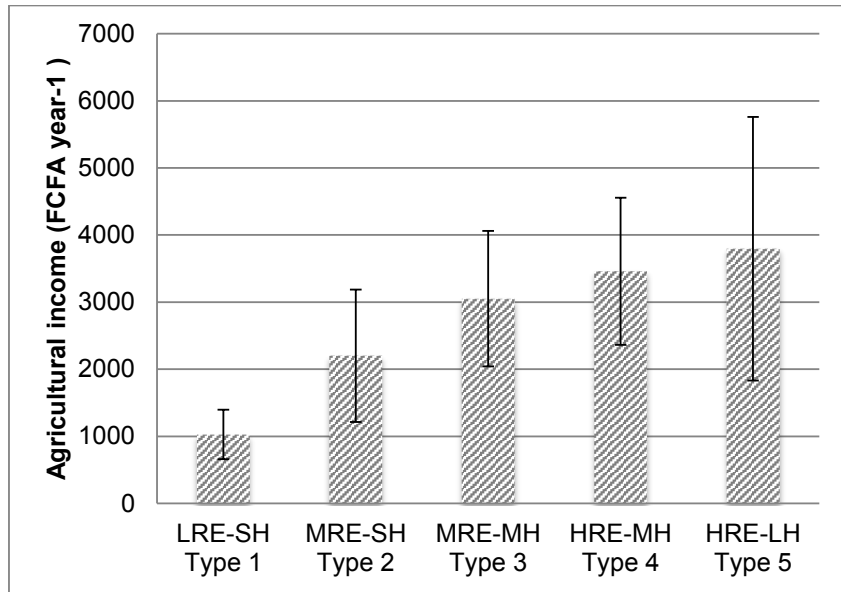
	June	July	August	September	October	November	December	January	February	March	April	May
Climatic season	Wet season				Cool dry season				Hot dry season			
Millet cropping	++	++	++	++	++	++	++	+				+
Groundnut cropping		+	++	++	++	+						
Presence of transhumant herd	+						+	++	++	++		
Grazing periods in fallow (Diohine)		+	++	++	++	++	+					
Bovine fattening (Barry)	++	+				+	++	++	++	++	++	++
Ovine fattening (Barry)		+	++	++	++							
Religious Muslim events (in 2012)			Korité X		Tabaski X	Tamkhalet X		Magal X				

895

896 Figure 4. Livestock farming and cropping practices intensity described as a function of the seasons in
897 the Niakhar region in the former groundnut basin of Senegal

898 *2 columns*

899



900

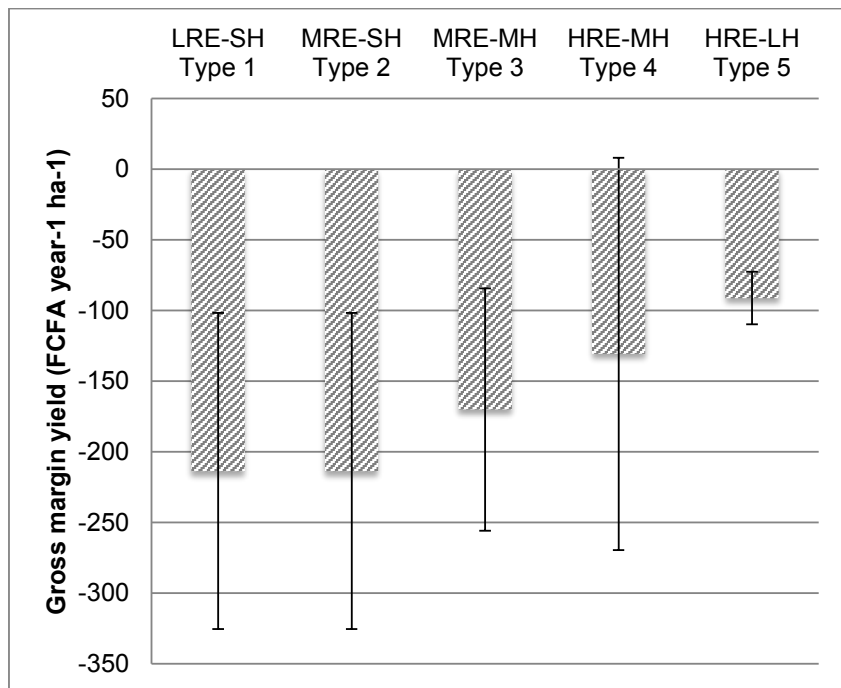
901 Figure 5: Agricultural income in the 2012-2013 cropping season according to the type of household

902

(1-5)

903 1.5 column

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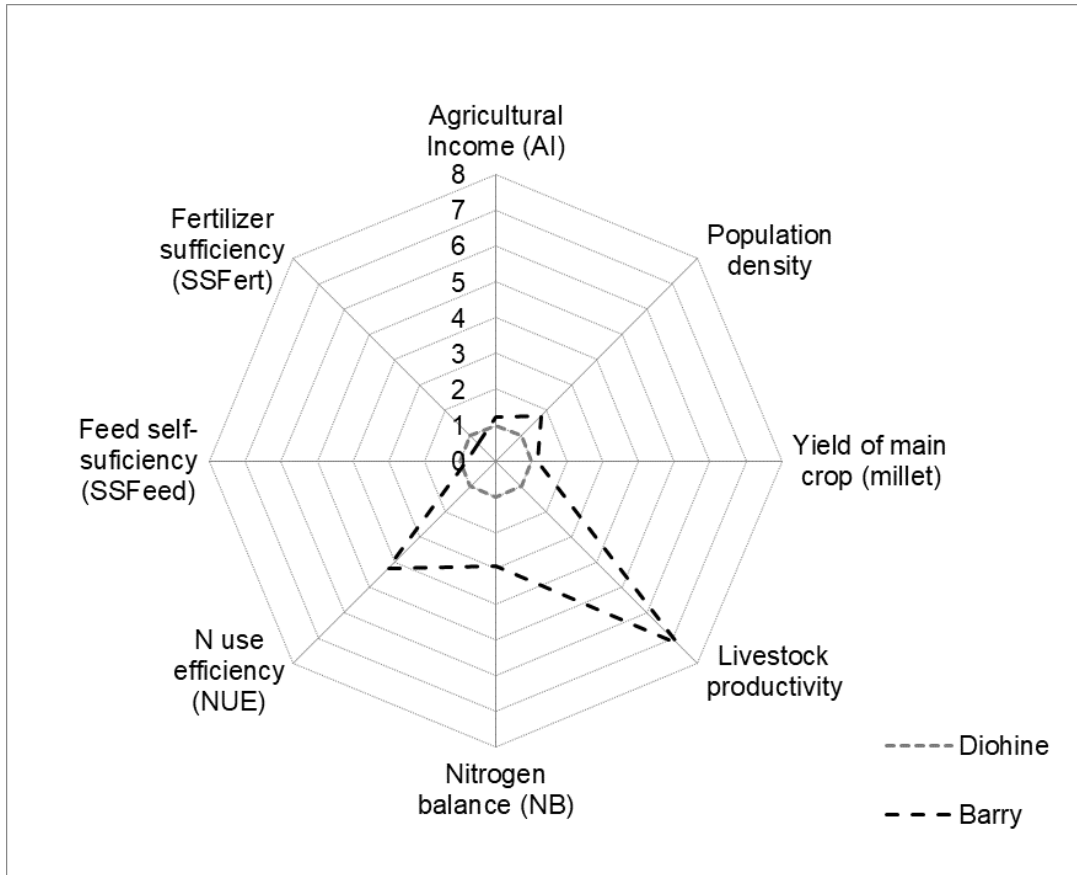
906 Figure 6: Average gross margin yield according to the type of household in the 2012-2013 cropping

907

season

908 1.5 column

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911 Figure 7: Synthesis of the main sustainability indicators at village *terroir* level for Diohine and Barry

912

in 2012

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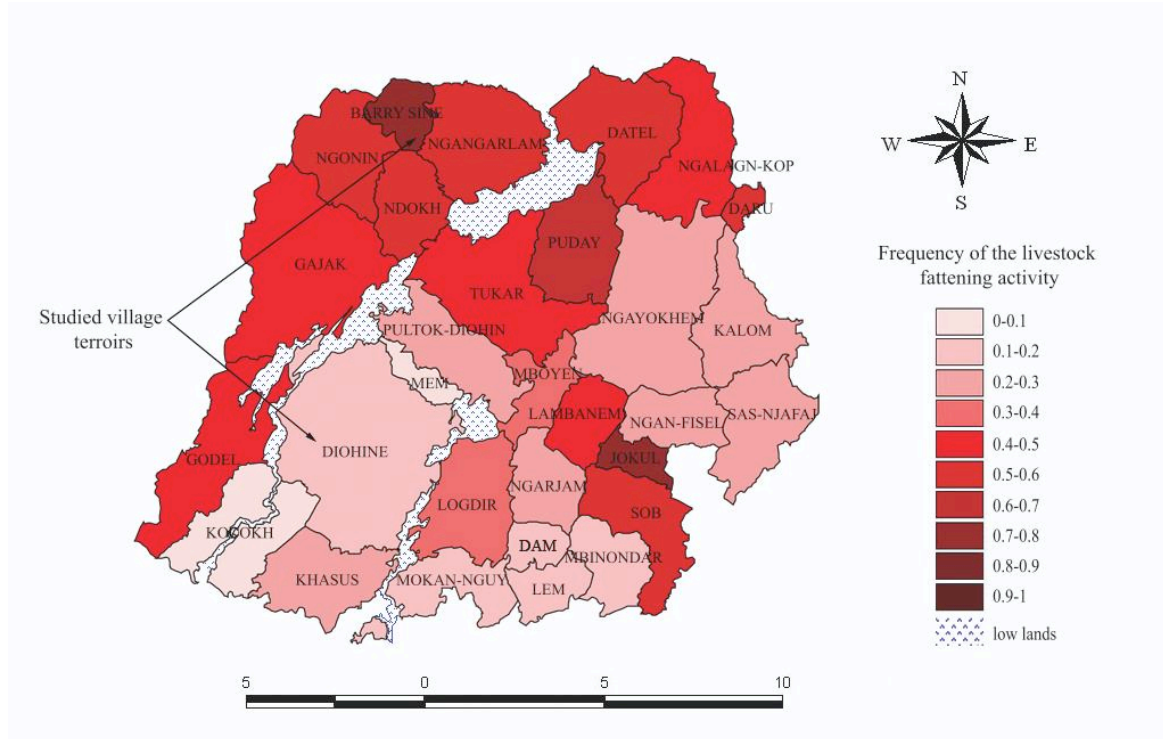


Figure 1. Portion of holdings that practice livestock fattening in 2012 in the 30 village *terroirs* of the Niakhar demographic and health observatory (Delaunay et Lalou, 2012).

2 columns, color

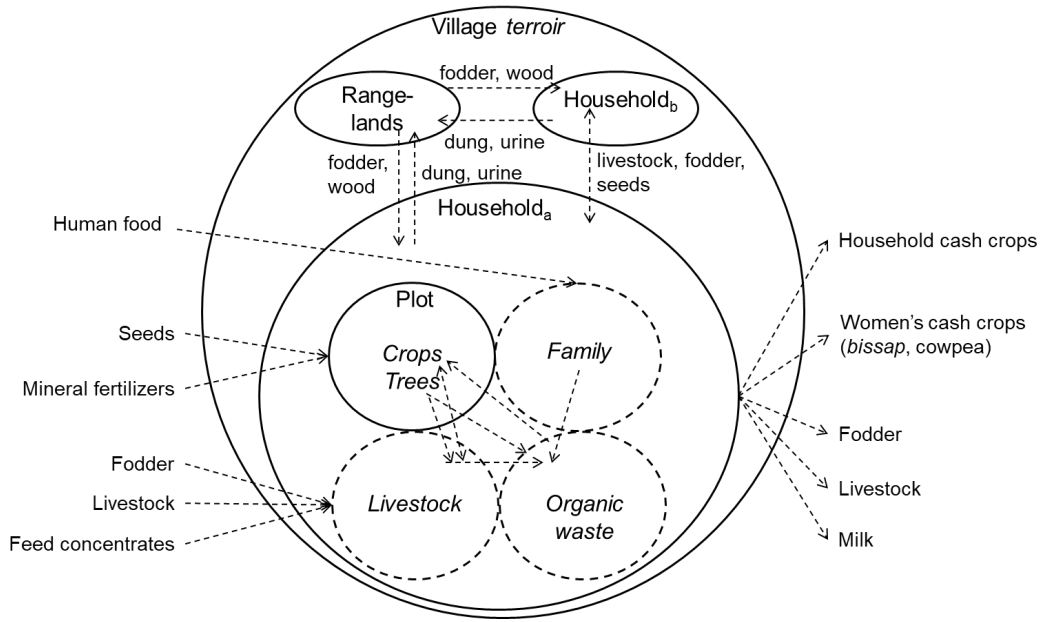


Figure 2. Conceptual stock-flow model of the system studied with three interlocking systems: plot, household and village *terroir*

1.5 columns

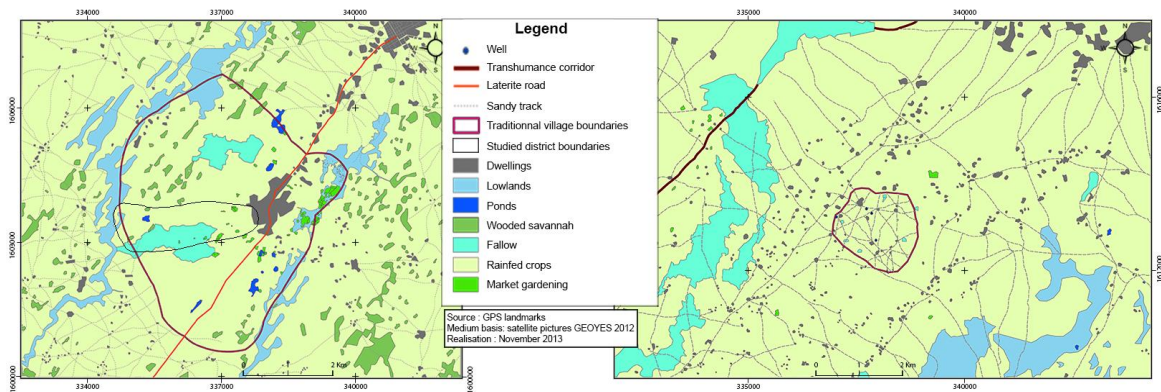


Figure 3. Agro-ecological zoning of Diahine (left) and Barry (right) during the 2012-2013 cropping season.

2 columns, color

	June	July	August	September	October	November	December	January	February	March	April	May
Climatic season	Wet season				Cool dry season				Hot dry season			
Millet cropping	++	++	++	++	++	++	++	+				+
Groundnut cropping		+	++	++	+							
Presence of transhumant herd	+						+	++	++	++		
Grazing periods in fallow (Diohine)		+	++	++	++	++	+					
Bovine fattening (Barry)	++	+				+	++	++	++	++	++	++
Ovine fattening (Barry)		+	++	++	++							
Religious Muslim events (in 2012)			Korité X		Tabaski X	Tamkhalet X		Magal X				

Figure 4. Livestock farming and cropping practices intensity described as a function of the seasons in the Niakhar region in the former groundnut basin of Senegal

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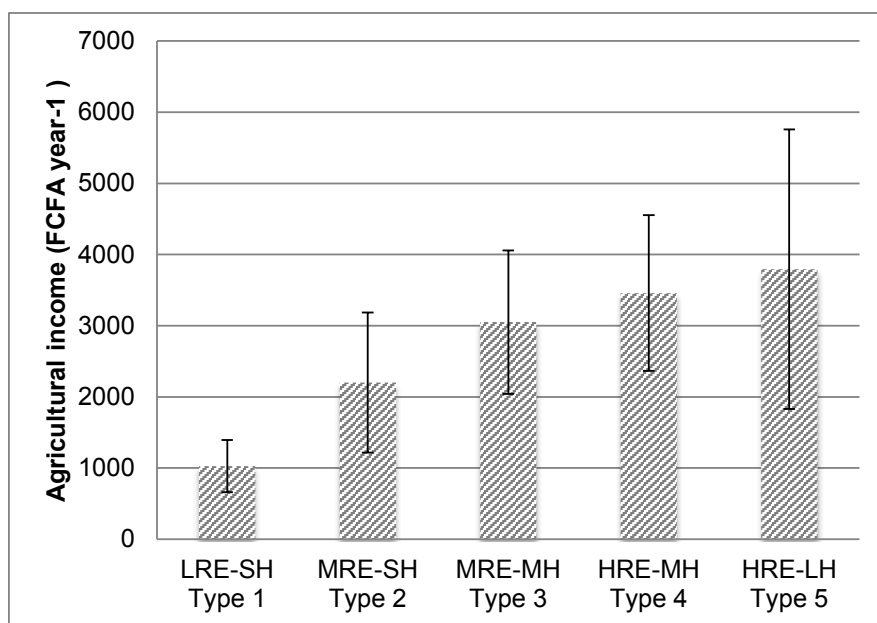


Figure 5: Agricultural income in the 2012-2013 cropping season according to the type of household

(1-5)

1.5 column

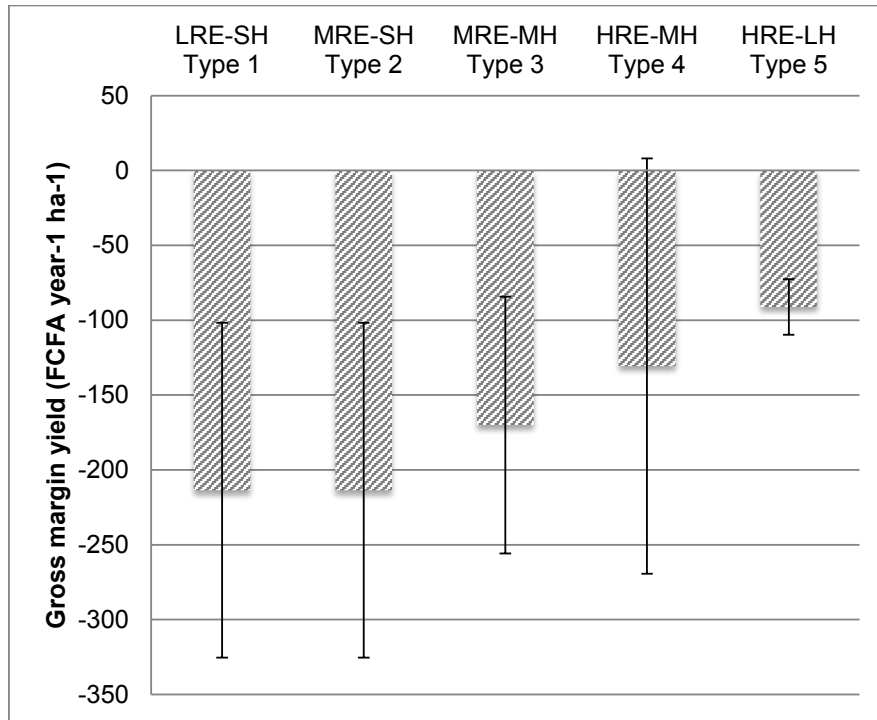


Figure 6: Average gross margin yield according to the type of household in the 2012-2013 cropping

season

1.5 column

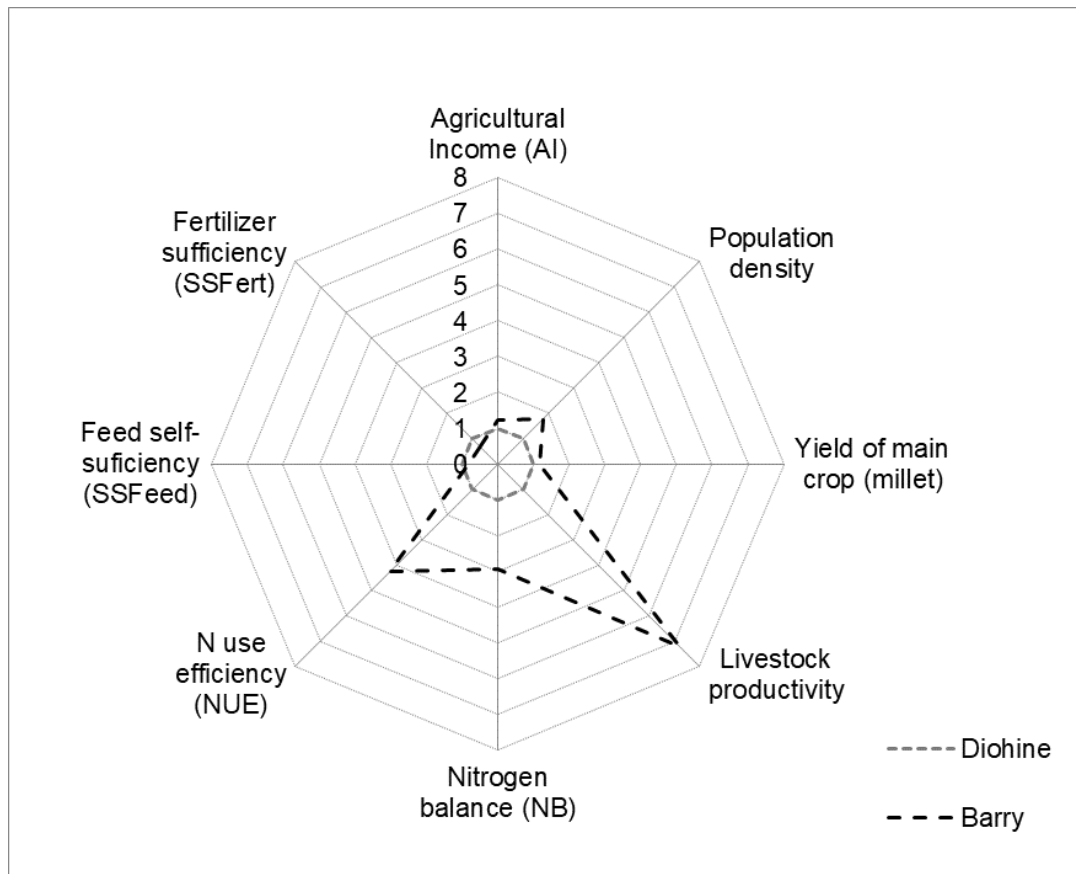


Figure 7: Synthesis of the main sustainability indicators at village *terroir* level for Diohine and Barry in 2012

1.5 column

Table 1. Main features of the five types of household in Diohine and Barry

Number given to type		1	2	3	4	5
Code name of type		LRE-SH	MRE-SH	MRE-MH	HRE-MH	HRE-LH
Livestock stocking rate	TLU ha ⁻¹	1.3	1.3	3.1	3.6	3.7
Importance of livestock fattening	% of total TLU	23	15	32	03	59
Population density	capita ha ⁻¹	4.5	2.8	4.2	3.1	6.3
Total cultivated area	ha	3.8	5.5	5.2	5.3	4.9
Importance of groundnut	% of TCA	26	19	32	8	20
Importance of fallow	% of TCA	2	11	2	19	0
Free-grazing plant biomass balance (Δ FG)	kgDM ha ⁻¹ year ⁻¹	-225	-61	-2	3451	-566
Manure inputs during night corralling	kgDM ha ⁻¹ year ⁻¹	113	25	218	758	323
Free-grazing and night corralling balance	kgN ha ⁻¹ year ⁻¹	0.15	2.99	8.43	3.69	9.93
Availability of solid manure from livestock housed in barns	TLU.h	24843	19431	49274	12505	95522
Solid manure input rate per livestock tethered close to the homestead	kgN TLU.h ⁻¹	0.00030	0.00063	0.00040	0.00055	0.00012
Nitrogen balance at household level	kgN ha ⁻¹ year ⁻¹	52.6	-0.2	42.4	43.0	151.0
Percentage of household in Diohine	%	11	78	0	11	0
Percentage of household in Barry	%	26	49	19	0	6

Table 2. Main indicators of crop fertilization at plot level, average results for the total cultivated area (TCA) in Diohine and Barry for the 2012-2013 cropping season

Indicator	Units	Diohine	Barry
<i>Herd-driven deposition of excreta during free grazing</i>			
Rate of deposition during free grazing	% IN	46	25
Balance of flows driven by free-grazing livestock- in the wet season	kgN ha ⁻¹	-8.32	-26
Balance of flows driven by free-grazing livestock- in the dry season	kgN ha ⁻¹	0.55	5.04
<i>Herd-driven deposition during night corralling</i>			
Input rate during night corralling in the wet and dry season	% IN	15	15
Night corralling area in the wet season	% TCA	2.7	0.2
Deposition of excreta during night corralling in the wet season	kgDM ha ⁻¹	83	20
Night corralling area in the dry season	% TCA	3	39
Deposition of excreta during night corralling in the dry season	kgDM ha ⁻¹	51	204
<i>Human application of solid manure</i>			
Inputs of solid manure as a percentage of total inputs	% IN	14	12
Area of application of solid manure	% TCA	22	31
Volume of manure applied	kgDM ha ⁻¹	337	482
<i>Human application of mineral fertilizer</i>			
Inputs of mineral fertilizer as a percentage of total inputs	% IN	8	27
Area of application of mineral fertilizer	% TCA	2	27
Volume of mineral fertilizer applied	kgN ha ⁻¹	1.09	6.28
<i>Human application of waste</i>			
Waste inputs as a percentage of total inputs	% IN	14	16
Area of application of waste	% TCA		
Volume of waste applied	kgN ha ⁻¹	1.86	3.75
<i>Human application of seeds</i>			
Seeds input as a percentage of total inputs	% IN	3	6
Area of application of seeds	% TCA	100	100
Volume of seeds applied	kgN ha ⁻¹	0.47	1.30

Table 3. Yields of main crop -products and by-products at plot level; Proportion of by-products left on the ground for the 2012-2013 cropping season in Diohine and Barry.

Indicator	Units	Diohine	Barry
<i>Yields of main products</i>			
Millet ear	kgDM ha ⁻¹	626	727
Sorghum ear	kgDM ha ⁻¹	480	779
Groundnut pod	kgDM ha ⁻¹	371	366
<i>Byproducts yields</i>			
Millet straw	kgDM ha ⁻¹	1 823	2 418
Sorghum straw	kgDM ha ⁻¹	1 067	2 505
Groundnut hay	kgDM ha ⁻¹	1 171	696
<i>Proportion of by-products left on the grounds</i>			
Millet	%	60	43
Sorghum	%	44	13
Groundnut	%	31	0

Table 4. N flows entering, leaving, and circulating within village *terroirs* and corresponding N-flow-based indicators at village *terroir* level for Diohine and Barry for the 2012-2013 cropping season

	Units	Diohine	Barry
<i>Input flows</i>			
Human food	kgN ha ⁻¹	3.73	4.85
Seeds	kgN ha ⁻¹	0.21	0.38
Mineral fertilizers	kgN ha ⁻¹	0.92	5.16
Direct withdrawal biomass ¹	kgN ha ⁻¹	0.74	0.88
Livestock	kgN ha ⁻¹	0.60	33.51
Fodder	kgN ha ⁻¹	0.22	0.37
Feed concentrates	kgN ha ⁻¹	3.39	23.67
<i>Output flows</i>			
Main crop products	kgN ha ⁻¹	0.11	0.88
Crop by-products	kgN ha ⁻¹	0.02	0.12
Livestock	kgN ha ⁻¹	1.00	42.48
Milk	kgN ha ⁻¹	0.00	0.37
Manure and urine	kgN ha ⁻¹	0.31	0.10
<i>Summary of flows</i>			
Total inputs (IN)	kgN ha ⁻¹	10.06	68.82
Total outputs (ON)	kgN ha ⁻¹	1.55	43.95
Total system throughflow (TST)	kgN ha ⁻¹	14.14	18.02
Dependence (D=IN/TST)	dmnl	2.03	12.66
SSFeed	%	86	70
SSFert	%	96	67
N balance (NB)	kg ha ⁻¹	8.51	24.88
N use efficiency (NUE)	dmnl	0.15	0.64

¹ Free grazing of plant biomass outside the boundaries of the village