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1 **Review: Role of herbivores in sustainable agriculture in sub-Saharan Africa**

2 A.A. Ayantunde^{1a}, A.J. Duncan², M.T. van Wijk³, P. Thorne²

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4 *¹International Livestock Research Institute (ILRI), 01 BP 1496, Ouagadougou, Burkina*
5 *Faso;*

6 *²International Livestock Research Institute (ILRI), PO Box 5689 Addis Ababa, Ethiopia;*

7 *³International Livestock Research Institute (ILRI), PO Box 30709, 00100 Nairobi, Kenya*

8 ^aCorresponding author: Augustine Ayantunde; E-mail: a.ayantunde@cgiar.org

9

10 Short title: Role of herbivores in sustainable agriculture

11 .

12 **Abstract**

13

14 The role of herbivorous livestock in supporting the sustainability of the farming systems
15 in which they are found is complex and sometimes conflicting. In sub-Saharan Africa
16 (SSA), the integration of livestock into farming systems is important for sustainable
17 agriculture as the recycling of nutrients for crop production through returns of animal
18 manure is a central element of the dominant mixed crop-livestock systems. Sustainable
19 agriculture has been widely advocated as the main practical pathway to address the
20 challenge of meeting the food needs of the rapidly growing population in SSA while
21 safeguarding the needs of future generations. The objective of this paper is to review the
22 state of knowledge of the role of herbivores in sustainable intensification of key farming
23 systems in SSA. The pathways to sustainable agriculture in SSA include intensification
24 of production and livelihood diversification. Sustainable agricultural practices in SSA have
25 focused on intensification practices which aim to increase the output : input ratio through
26 increasing use of inputs, introduction of new inputs or use of existing inputs in a new way.
27 Intensification of livestock production can occur through increased and improved fodder
28 availability, genetic production gains, improved crop residue use and better nutrient
29 recycling of manure. Livestock deliver many “goods” in smallholder farming systems in
30 SSA including improving food and nutrition security, increased recycling of organic matter
31 and nutrients and the associated soil fertility amendments, adding value to crop residues
32 by turning them into nutrient-rich foods, income generation and animal traction. Narratives
33 on livestock “bads” or negative environmental consequences have been largely shaped
34 by the production conditions in the Global North but livestock production in SSA is a
35 different story. In SSA, livestock are an integral component of mixed farming systems and

36 they play key roles in supporting the livelihoods of much of the rural population. None-
37 the-less, the environmental consequences of livestock production on the continent cannot
38 be ignored. To enhance agricultural sustainability in SSA, the challenge is to optimize
39 livestock's role in the farming systems by maximizing livestock "goods" while minimizing
40 the "bads". This can be through better integration of livestock into the farming systems,
41 efficient nutrient management systems, and provision of necessary policy and institutional
42 support.

43

44 Keywords: sustainable intensification, smallholder farming systems, ruminant livestock,
45 food security; trade-off

46

47 **Implications**

48

49 This review shows that the role of livestock in agricultural sustainability in sub-Saharan
50 Africa (SSA) is complex and conflicting. In view of the marked diversity in biophysical and
51 socio-economic contexts of smallholder crop-livestock farmers in SSA, the concept of
52 sustainable agriculture has to be adapted to varied local values and constraints. Livestock
53 deliver a range of "goods" in the dominant smallholder mixed crop and livestock systems
54 in Africa, therefore the over-emphasis on the environment is simplistic and should be
55 moderated by the enormous importance of livestock in generating food security for some
56 of the more vulnerable people in the world.

57

58 **Introduction**

59

60 The dominant herbivores in Sub-Saharan African farming systems are ruminants (cattle,
61 sheep and goats). Cattle are considered critical for sustainable agriculture in Africa as the
62 main source of manure and draught power for crop production. In addition to the
63 importance of ruminants in nutrient cycling, they fulfil many socio-cultural functions in the
64 livelihoods of smallholder farmers in sub-Saharan Africa such as storage of wealth,
65 source of dowry payment, particularly among the pastoral societies, and as a risk aversion
66 strategy in mixed crop-livestock systems (Vall *et al.*, 2017). Owning livestock is critical for
67 household food security in many African countries. The livestock production systems of
68 SSA are largely defined by pastoral systems dominant in the hyper-arid and arid zones,
69 and mixed crop-livestock systems which dominate in the semi-arid and sub-humid zones
70 (Table 1). Even within a specific livestock system however, livestock keepers are not
71 homogenous as they differ in terms of livestock assets, socio-economic endowment and
72 cultural ties to livestock (Vall *et al.*, 2017).

73 There is general consensus around the important role that herbivorous livestock
74 play in the sustainability of the farming systems in which they are found, although there
75 is some debate around the specifics of their positive and negative contributions. Ensuring
76 that herbivores make a net positive contribution to sustainability requires livestock
77 managers to carefully balance their positive and negative impacts. Integration of livestock
78 into farming systems permits recycling of nutrients from crop residues into animal manure
79 which acts as an essential nutrient source for crop production. This is a hallmark of mixed
80 crop and livestock systems (Pretty *et al.*, 2011; Rudel *et al.*, 2016) and one that
81 contributes significantly to overall system sustainability by reducing the need for external

82 inputs. Livestock, and particularly ruminants, traditionally graze on natural pasture, forest
83 areas, roadsides, fallow lands, crop re-growth or residues such as straws, legume
84 haulms, and other by-products, thereby allowing more efficient use of land than if it were
85 only cropped. For example, the keeping of livestock has been essential for survival in
86 divergent systems such as those of the agro-pastoralists in SSA, and animals have long
87 been essential for sustaining crop yields in the infield–outfield systems of West and
88 Eastern Africa, where dung and draught from wasteland grazing (outfields) is used for
89 crop cultivation on the infields around the homesteads (e.g. Schiere *et al.*, 2002; Giller *et*
90 *al.*, 2011).

91 The objective of this paper is to review the state of knowledge regarding the role
92 of herbivores in the sustainable intensification of key farming systems in SSA. In this
93 paper we will argue that the over-emphasis on the environmental consequences of
94 livestock production is simplistic and should be moderated by the enormous importance
95 of livestock in generating food security for some of the more vulnerable people in the
96 world and other livestock “goods” or benefits in smallholder farming systems in SSA.

97

98 **Sustainable agriculture – definition of concept and need**

99

100 The concept of sustainability is increasingly recognized as a desirable, if not essential,
101 outcome in many areas of agricultural research. However, researchers often struggle to
102 define it when challenged to do so. Indeed, Pretty *et al.* (2011) draw attention to more
103 than 100 different ways of defining sustainability and it can be concluded from this *pot*
104 *pourri* that there is no one definition to fit all possible scenarios. The umbrella definition
105 of sustainable development, going back to 1978, is perhaps that of the World Commission

106 on Environment and Development (also known as the Brundtland Commission), namely
107 “development that meets the needs of the present without compromising the ability of
108 future generations to meet their own needs”. Whilst there are many subtleties that are not
109 captured by this definition, it does serve to emphasize the essential element of
110 considering the implications of current practice for future generations as well as our own.

111 The concept of sustainable agriculture essentially follows the key principles
112 inherent in sustainable development. Rudel *et al.* (2016) defined sustainable agriculture
113 as producing enough food for consumers and enough income for farmers while
114 maintaining agro-ecosystem services. National Research Council (NRC) 2010) in its
115 publication “Toward Sustainable Agricultural Systems in the 21st Century” defined
116 sustainable agriculture as agriculture that satisfies human food, feed and fibre needs;
117 enhances environmental quality and the resource base; sustains economic viability and
118 enhances the quality of life for farmers, farm workers and society as a whole. From these
119 various definitions, the common elements of sustainable agriculture include food
120 production for both present and future needs, persistence of the systems (that is, capacity
121 to continue to produce desired outputs over long periods), resilience (ability to absorb
122 shocks and stresses, and deliver the desired outputs) and environmental friendliness.
123 (Schiere *et al.*, 2002; Pretty *et al.*, 2011). Nonetheless, the concept of agricultural
124 sustainability inherently lacks specificity. Approaches to overcoming this difficulty usually
125 centre around the definition of indicators and metrics (Smith *et al.*, 2017) that the evidence
126 suggests are likely to be reliably associated with ultimately sustainable outcomes.

127 In view of marked diversity in biophysical and socio-economic contexts of
128 smallholder crop-livestock farmers in sub-Saharan Africa, the concept of sustainable

129 agriculture has to be adapted to varied local values and constraints. This implies that
130 agricultural practices that can be regarded as sustainable in one region may not be
131 sustainable in another. In this paper, we will adopt as a working definition of sustainable
132 agriculture, "*agriculture that is sufficiently productive to meet food needs in both short and*
133 *long-terms, and that is economically viable, environmentally friendly and socially*
134 *acceptable*" (NRC, 2010; Schiere *et al.*, 2002).

135

136 **The role of livestock in sustainable agriculture in sub-Saharan Africa**

137

138 In sub-Saharan Africa, sustainable agricultural practices have focused on intensification
139 practices which aim to increase the efficiency (output : input ratio) of production systems.
140 Intensification of farming systems will depend on factors such as farmers' agro-ecological
141 potential, economic conditions, market situation, policy environment, institutional capacity
142 and available technological options (Gunton *et al.*, 2016). Tactics for intensification
143 include increasing use of inputs, introduction of new inputs to the system, and or use of
144 existing inputs in a new way (Pretty *et al.*, 2011) provided that these changes result in a
145 disproportionate increase in associated outputs. Some common intensification practices
146 in mixed crop and livestock systems include application of inorganic fertilizer, use of
147 improved seed, conservation agriculture and small-scale mechanization alongside
148 animal-related interventions such as animal traction, animal manure use, improved
149 breeds and improved feeding practices (Table 2). Generally, capital-intensive
150 intensification options are not widely adopted in sub-Saharan Africa due to the obvious
151 constraint of lack of financial resources (Vall *et al.*, 2017).

152 Application of animal manure to cropped land is widely practiced in sub-Saharan
153 Africa and there is widespread evidence of beneficial effects on grain yield and soil fertility
154 (Vall *et al.*, 2017). Application of animal manure is normally pivotal in mixed crop-livestock
155 systems. In African Drylands, often only manured crop fields are in positive nutrient
156 balance as shown by results of a study of livestock-mediated nutrient transfers from
157 south-western Niger (Hiernaux and Ayantunde, 2004; Table 3). The main constraints to
158 manure application is always inadequate quantity due to low animal numbers and a
159 shortage of labour for distributing the manure.

160 Associated with peri-urban dairy production in many African countries is the use of
161 improved dairy cows (Anderson, 2003; Paul *et al.*, 2018) which produce more milk than
162 local breeds provided they are well fed. For example in Rwanda, the government provided
163 crossbred cow to poor farmers under the “one cow per poor family” program which aims
164 to improve food and nutrition security, and reducing poverty (Paul *et al.*, 2018). The
165 crossbred cows produced 2 – 4 litre/cow/day compared to 2 litre/cow/day for the local
166 breed (Paul *et al.*, 2018). While crossbreds make a big difference to yield potential, there
167 are relatively few examples of economically sustainable practices that allow that potential
168 to be realised. The main constraint to more widespread use of improved livestock breeds
169 is lack of artificial insemination, high feed requirements of the improved breeds, reduced
170 disease resistance and lack of necessary animal husbandry skills.

171 Use of animals (bull, oxen, horse and donkey) for traction is also a common
172 practice in mixed crop and livestock systems in SSA (Savadogo *et al.*, 1998; Sheahan
173 and Barrett, 2017). Animal traction is widely practiced to plough crop field and for weeding
174 in many farming systems in SSA, particularly for cash crops such as cotton in West

175 African Sahel. Lack of bulls, particularly in West Africa, and high feed requirements are
176 often the constraints to use of animal traction in mixed crop and livestock systems.

177 Food security is an urgent and immediate challenge in sub-Saharan Africa due to
178 a rapidly growing population coupled with lagging agricultural growth (The Montpellier
179 Panel, 2013). Addressing this challenge requires sustainable agricultural practices and
180 choices to significantly increase yields on existing agricultural land. Livestock have an
181 important role to play in enhancing food security and particularly nutritional security.
182 Although there is increasing consumption of animal source food in the human diet in many
183 countries in sub-Saharan Africa (such as Burkina Faso, Ghana, Ethiopia, Kenya; Food
184 and Agriculture Organization of the United Nations (FAO), 2011), the diet is still largely
185 dominated by the intake of basic cereal-based staple foods which are usually deficient in
186 protein and micro-nutrients necessary for healthy human development (Reynolds *et al.*,
187 2015). The consumption of animal products is closely related to per capita income with
188 the urban population consuming higher amounts of animal protein due to their growing
189 financial means. Consumption of animal protein is particularly important for children under
190 5 years and women of reproductive age. The importance of consumption of animal source
191 food for cognitive development of children is well documented (Fan and Brzeska, 2016).
192 For example, a nutritional study in Gourma in the Northern part of Mali showed that the
193 children of mobile pastoralists were better nourished based on weight-height, weight-age
194 and height-age measures than children of sedentary farmers (Pederson and
195 Benjaminsen, 2008). This difference was largely attributed to consumption of milk and
196 milk products by the pastoralist children underscoring the important role that livestock
197 play in human nutrition. Households that keep livestock are more likely to consume

198 animal-source food because of their proximity to these nutrient-rich foods (Reynolds *et*
199 *al.*, 2015). Increased consumption of animal-source food by rural households reduces
200 stunting in children and improves the health of household members, particularly children
201 and vulnerable women (Pederson and Benjaminsen, 2008). One pathway to improve the
202 consumption of animal protein is through improvements in livestock production.
203 Agricultural production practices that lead to increased grain and livestock productivity
204 will likely impact positively on food security as observed by the respondents in a survey
205 in two provinces in Burkina Faso regarding the impact of intensification practices on
206 household food security (Figure 1).

207 Household survey data show that another key food security role of livestock is in
208 generating income, so that food can be bought throughout the year. Families that keep
209 few livestock are the most vulnerable to food shortages based on evidence from surveys
210 in mixed crop-livestock systems in four countries in West Africa (Figure 2). In Figure 3,
211 (after Ritzema *et al.*, 2017) at contrasting sites in Burkina Faso, Ethiopia and Kenya, the
212 relative importance of on- and off-farm activities for food security is quantified, illustrating
213 that both consumption and sales of livestock products are essential for food security. In
214 the agro-pastoral region in Borana, southern Ethiopia, direct consumption of livestock
215 products plays a dominant role in livelihoods, while in the other sites, sales of livestock
216 products are important for cash generation. These results also show that the most food
217 secure households are also typically the households with most livestock and therefore
218 the highest importance of livestock products in their livelihood compared to the other food
219 security groups.

220

221 **Drivers of sustainable agriculture in sub-Saharan Africa and some constraints**

222

223 Population growth, climate change and natural resource availability (land and water) are
224 the main drivers of sustainable intensification in SSA (Pretty *et al.*, 2011). There is a need
225 to produce more food on less land to meet the growing food demand of the population,
226 but this must be done in a way that does not undermine environmental integrity. The
227 average annual population growth rate of 2.7% in SSA has led to the challenge of feeding
228 more people which necessitates an increase in agricultural production (The Montpellier
229 Panel, 2013).

230 Climate change and variability has compelled farmers to diversify species
231 composition of their herds (Vall *et al.*, 2017; Zougmore *et al.*, 2016). For example,
232 repeated occurrence of droughts in the Sahel has led many pastoralists, who were once
233 solely dependent on livestock for their livelihoods, to adopt agro-pastoralism (that is,
234 rearing livestock and growing crops; Zougmore *et al.*, 2016). In response to climate
235 change, many crop farmers have also diversified in the past two decades into rearing
236 livestock due to repeated crop failure associated with droughts (Zougmore *et al.*, 2016).
237 Investment in irrigation has been advocated as a potential “game changer” in improving
238 agricultural productivity in view of the present very low irrigated area (4% of the cultivated
239 land) in Africa (The Montpellier Panel, 2013).

240 Some barriers to sustainable intensification in SSA include lack of policy support
241 to smallholder farmers (Garnett *et al.*, 2013), a dysfunctional institutional environment
242 (Houkounou *et al.*, 2012), market failures, lack of appropriate productivity enhancing
243 agricultural technologies and low adoption where they are available, lack of access to
244 credit, low use of external inputs and poverty leading to short-termism among farmers.

245 The policy (local, national and regional) and institutional environment (customary and
246 modern) are key to sustainable agriculture in SSA. At continent level, the policy initiative
247 of the African Governments to increase agricultural productivity known as the
248 Comprehensive Africa Agriculture Development Programme (CAADP) has set a target of
249 six *per cent* annual agricultural productivity growth rate. To achieve this target it has been
250 recommended that 10 *per cent* of the annual budget of each country should be spent on
251 the agriculture sector at the Maputo Declaration (New Partnership for Africa's
252 Development (NEPAD), 2003). This increased policy attention to agricultural growth is a
253 welcome spur to agricultural intensification in Africa although the implementation may be
254 lagging behind. Institutional issues that can impact on agricultural sustainability in SSA
255 include natural resource governance, knowledge institutions (agricultural research and
256 local institutions) and stakeholders' organizations, particularly farmers'
257 networks/associations. Other factors such as insecurity and civil war, insecure land tenure
258 and water rights, weak agricultural extension systems, and underfunding of national
259 agricultural research systems further aggravate the difficulties facing agricultural
260 production in SSA (Douxchamps *et al.*, 2014).

261 Market development and the associated growing demand for agricultural products
262 (food e.g. grains, meat and milk; and processed food products) is another important factor
263 determining agricultural sustainability (Garnett *et al.*, 2013). This entails both more food
264 and value addition. The barrier to sustainable agriculture of low use of external inputs
265 could be attributed to extensive farming systems and the associated subsistence
266 orientation of crop and livestock farmers. Besides, low use of external inputs could be
267 due to poor financial resources among farmers, lack of access to external inputs and the

268 high price of the inputs where available confounded by high production risk, as agriculture
269 is largely rainfed in SSA, and high market risk. One opportunity to reduce the latter risk is
270 the rapidly increasing availability of mobile phone technology. Increased use of mobile
271 phones has facilitated real-time access to market information particularly prices of
272 agricultural products (grains and live animals) which is influencing the decision of many
273 rural farmers on when and where to sell their produce (Sheahan and Barrett, 2017).

274

275 **Livestock-related intensification practices in sub-Saharan Africa: pathways to** 276 **sustainable agriculture**

277

278 Intensification of agricultural production has been widely advocated as the key pathway
279 to sustainable agriculture in Africa. There is great potential for intensification of crop and
280 livestock production in view of the current low productivity and high productivity gap
281 (Gunton *et al.*, 2016). For intensification to be sustainable, Pretty *et al.* (2011) suggested
282 a number of criteria including efficient and prudent use of inputs, minimizing greenhouse
283 gas emissions or environmental costs, increasing the flow of environmental services and
284 strengthening resilience. A well-known conceptual example of livestock intensification is
285 the so-called livestock ladder (Udo *et al.*, 2011), which describes a theoretical system that
286 poor smallholders can use to step up from keeping small-stock to acquiring larger
287 animals. Continued re-investment in the agricultural system is needed in the lowest parts
288 of ladder, plus the availability of fodder to feed the growing stock. According to these
289 authors, the economic benefits derived from livestock intensification depends on the rung
290 of the ladder where the farmers are located. Thus, the smallest economic benefits will

291 come from village poultry, followed by small ruminants, pigs and local cattle while the
292 largest economic benefit will come from dairy cattle.

293 The livestock ladder gives a conceptual model of change in livestock holdings over
294 time, but in practice the resource-constrained smallholder crop and livestock farmers in
295 sub-Saharan Africa can directly potentially increase their livestock production (produce
296 more per given land area and per unit livestock) through adoption of appropriate
297 technological, social and institutional innovations, and through improvement of farmers'
298 knowledge and capacity, and better market access (Pretty *et al.*, 2011). For example,
299 Amole *et al.* (2017) have shown through a simulation model of West Africa Dwarf goats
300 production that with improved feeding management such as grazing with supplementation
301 or cut-and-carry feeding systems, the pre-weaning growth rate of kids can be doubled
302 and the pre-weaning mortality can be reduced from about 26% in the traditional free range
303 feeding system to between 5 and 12% in improved feeding systems. Similar results of
304 increased animal productivity have been reported with improved feeding systems in
305 smallholder dairy production in East Africa (Bebe *et al.*, 2002). In Ethiopia, yield gap
306 analyses of attainable milk yield by cows showed that replacing indigenous zebu with
307 crossbred cattle could lead to doubling of milk yields, even on traditional diets, and to a
308 profitable smallholder dairy enterprise (Mayberry *et al.*, 2017). This demonstrates that
309 there is great potential for livestock productivity and economic gains through more
310 intensive livestock production.

311 The growing demand for livestock products particularly in urban areas also
312 provides opportunity for the intensification of livestock production. Consumption of
313 livestock products has been increasing over the years in all regions in sub-Saharan Africa

314 and these trends are expected to continue in the foreseeable future. For example, in West
315 Africa, the current annual growth rates in livestock commodity consumption (2.7% for
316 mutton, 4% for poultry, 2.9% for milk, and 3.3% for beef; FAO, 2011) are much higher
317 than for cereals (about 2%). The growing demand for consumption of animal source food
318 has been driven partly by rapidly growing cities, potentially opening up avenues to bridge
319 nutritional gaps, as well as providing incomes and livelihoods for the population, including
320 for target groups such as the poor, women and youth. In addition, the growing demand
321 has also been driven by the improved regional economic performance in the last few
322 decades, moving from the negative GDP growth rates observed in the early 1980s to
323 annual growth rates that have remained positive since then. Though there will be
324 continued growth in per-capita demand for livestock products in West Africa and other
325 regions in Africa from 2000 to 2030, the absolute increase in annual per-capita
326 consumption (in kg/person) during this period is still low compared to regions in Asia
327 (FAO, 2011).

328 Another opportunity for sustainable agriculture in sub-Saharan Africa is the
329 increasing integration of crop and livestock production, though the level of integration may
330 vary depending on the agro-ecological potential, socio-economic endowment, production
331 objectives, natural resource base and local institutions. Better integration of crop and
332 livestock production could improve the efficiency of nutrient cycling in farming systems
333 and whole farm productivity (National Research Council, 2010; Vall *et al.*, 2017).
334 Integration of crop and livestock production provides opportunity for value addition to crop
335 residues by the livestock through conversion of “waste” products which cannot be
336 consumed by humans (crop residues) into nutrient-rich foods. The contribution of crop

337 residues to livestock diets will continue to increase in African farming systems depending
338 on the agro-ecological zone in view of the declining grazing areas due to expansion of
339 arable production, particularly in Africa drylands (Dongmo *et al.*, 2012) For example,
340 results from evaluation of feed resources in three countries in West Africa showed the
341 increasing contribution of crop residues to livestock diets as we move from sub-humid
342 zone (< 10%) to semi-arid zone (about 50%; Figure 4). Similar trends are seen in a recent
343 study in Ethiopia which assessed historical changes in feed sourcing across the pastoral
344 to highland gradient and pointed to increasing importance of crop residues in livestock
345 diets (Figure 5).

346 Better manure management also provides the opportunity to reduce GHG
347 emissions in addition to contributing to efficient nutrient cycling in the mixed crop and
348 livestock systems. Practices such as mulching or using cereal straws as beddings where
349 animals are corralled have resulted in better capture of faecal and urinary nitrogen
350 thereby reducing ammonia volatilization, which can be up 60% of excreted faeces and
351 urine (Hiernaux and Ayantunde, 2004). Besides, the association of mulching and
352 corraling of ruminants improves soil chemical properties which can lead to increase in
353 grain yield and crop residue biomass.

354 In addition to intensification, livelihood diversification is an important pathway to
355 sustainable agriculture in Africa. This can be defined as the process by which rural
356 families construct a diverse portfolio of activities and social support capabilities in order
357 to survive and to improve their standards of living (Ellis, 1998). According to Ellis,
358 diversification may occur both as a deliberate strategy by the household or be triggered
359 by crises such as climatic shocks. Diversification may concern on-farm or off-farm

360 activities. Off-farm activities such as small commerce, seasonal migration etc., provide
361 additional sources of revenue for rural households which may be invested in agricultural
362 production. Livestock play an important role in diversification strategies, because of their
363 diverse role in smallholder livelihoods: livestock produce food that can be directly
364 consumed, while livestock products are also sold to generate essential cash for
365 expenses. The livestock herd can also function as a flexible reserve for the farm
366 household. For example, the repeated occurrence of droughts in the West African Sahel
367 has led to significant shifts in herd composition from cattle to small ruminants (Zougmore
368 *et al.*, 2016). Diversification of agricultural production systems is often associated with
369 increased resilience of livelihoods and livestock can play a key role in the ability of
370 smallholder households to deal with shocks (for example, the ‘banking’ function of
371 livestock in case of severe droughts) when major food crops fail. Both intensification and
372 livelihood diversification pathways to sustainable agriculture are complementary. For
373 example, money from seasonal migration by members of the agro-pastoral households
374 is often invested in acquiring livestock and inputs for crop farming.

375

376

377 **Environmental consequences of livestock in sustainable agriculture**

378

379 In the previous sections we have stressed the ‘goods’ of livestock for sustainable
380 intensification and increased recycling of organic matter and nutrients: soil fertility
381 amendment through concentration of organic matter (either through grazing of crop
382 residues or common grasslands), including enhanced nutrient cycling; the essential role
383 of livestock in supplying traction and thereby the timely planting of crops at the start of the

384 growing season; and adding value to crop residues leading to increased system
385 productivity. In this section we will concentrate on the environmental consequences of
386 livestock in sustainable agriculture in sub-Saharan Africa.

387 Livestock have received much negative publicity in recent years for their impact on
388 the environment (Steinfeld *et al.*, 2006) and their role in disease transmission (Jones *et*
389 *al.*, 2008). Much of this negative messaging is influenced by livestock production practices
390 and food consumption patterns in the Global North. Industrial production practices have
391 serious environmental externalities including greenhouse gas emissions and pollution of
392 air and water. Much of the feed used in such systems could be more efficiently used if
393 directly consumed by humans (Wilkinson, 2011). Furthermore, levels of animal source
394 food consumption in the Global North are much higher than in the Global South and this
395 brings a range of health issues. Livestock production in SSA is a different story. In SSA,
396 livestock are an integral component of mixed system agriculture as indicated above. They
397 play key roles in the livelihoods of much of the rural population. None-the-less
398 environmental consequences of livestock production on the continent cannot be ignored.

399

400 *Greenhouse gas emissions*

401

402 Livestock are major contributors to greenhouse gas (GHG) emissions globally. The
403 publication from FAO on global assessment of emissions highlighted the considerable
404 GHG impact of livestock estimating that 14% of global GHG emissions arise from the
405 livestock sector (Gerber *et al.*, 2013). This includes emissions associated with feed
406 production including from land use change such as conversion of forests to grazing lands,
407 animal production (enteric emissions and emissions from manure) and transport of feed.

408 Livestock are increasingly viewed as a global bad with a strong lobby actively promoting
409 reduced per capita consumption of animal source foods in the developed world. In terms
410 of regional contributions to livestock-based GHG emissions, sub-Saharan Africa does
411 emerge as a hotspot. Recent work indicates that 75% of non-CO₂ emissions are
412 generated in the developing world with SSA responsible for a considerable share (Herrero
413 *et al.*, 2013). Expressing the numbers as emission intensities (emissions per unit of
414 livestock product) presents an even starker picture with SSA emerging as a region with
415 particularly high emission intensities. The high emission intensities in SSA are due largely
416 to low feed use efficiency with large numbers of livestock subsisting on low levels of
417 feeding and producing very low yields of milk and meat. Expressing GHG emissions per
418 unit of livestock products ignores the wider contribution of livestock to livelihoods in the
419 developing world. In SSA, cattle are kept for milk and meat but also for a range of other
420 farm functions including traction, financial security and production of organic fertilizer
421 among other uses (Hiernaux and Ayantunde, 2004). The narrow focus on emission
422 intensities has been pointed out in recent work where the denominator in the intensity
423 equation was broadened to include a range of livestock functions. Although based on a
424 small case study in Kenya, this work showed the much lower emission intensities that
425 emerge from a broader view of the contribution of livestock to farm livelihoods in the
426 developing world and point the way for more balanced assessments in future (Weiler *et*
427 *al.*, 2014).

428

429 *Negative effects of grazing*

430

431 Further negative effects of livestock are related to loss of biodiversity through overgrazing
432 and the associated environmental negative feedbacks (erosion, deforestation,
433 introduction of invasive species etc.) (Asner *et al.*, 2004). This partly relates to increased
434 human population pressure leading to encroachment of cropping into previous grazing
435 areas. This reduces availability of rangelands as traditional grazing reserves and
436 concentrates grazing on smaller areas with associated negative effects on rangeland
437 condition and biodiversity. Expansion of cropping into previous grazing reserves may also
438 have implications for release of the carbon currently locked up in pastures. Increased
439 grazing intensity alters competition between grass and browse species and can lead to
440 encroachment of grazing areas by shrubs and trees (D'Odorico *et al.*, 2012) which provide
441 less nutrition for domestic livestock (except perhaps goats). Furthermore, invasive shrubs
442 can radically alter species composition of grazing areas with negative effects on
443 rangeland quality. Domestic livestock can exacerbate the spread of invasive species
444 through transfer of seed and by altering competitive relationships with native species. A
445 further potentially negative effect of grazing is the transfer of nutrients from extensive
446 grazing areas by removal of biomass through grazing. In general, nutrients removed
447 through grazing are returned through excreta but where grazing livestock are corralled
448 overnight the cycle can be broken. Increased erosion can also be attributed to excessive
449 livestock grazing pressure. Soil loss can occur where heavy grazing pressure leads to
450 soil compaction reducing infiltration and increasing run-off. Furthermore, reduction in
451 biomass cover can expose soils to water and wind erosion with potentially serious
452 consequences for soil integrity.

453

454 *Water footprint*

455

456 In water-scarce environments that dominate parts of sub-Saharan Africa, water use is a
457 key issue and the use of water by livestock needs to be considered. The bulk of water
458 used to support livestock production is for production of feed. Livestock production
459 accounts for 31% of agricultural water use and of this portion, 90% is used in production
460 of feed. With increased demand for livestock products, the amount of water used for
461 livestock production is predicted to double by 2050 (Peden *et al.*, 2007). A key issue when
462 considering livestock water interactions is livestock water productivity, the amount of
463 livestock product (or financial benefit) per unit of water used in its production. Sub-
464 Saharan Africa is a hotspot for low livestock water productivity although, as for GHG
465 emissions, the wider benefits of livestock keeping in Africa than simply production of milk
466 and meat are sometimes ignored. Furthermore, there are dangers in comparing livestock
467 water productivities in industrialized systems in the Global North which rely on dedicated
468 feed production with those in the Global South where livestock feed is often produced in
469 areas unsuitable for arable production and where feed is often a by-product of human
470 food production.

471

472 **Trade-offs associated with livestock's roles in sustainable agriculture**

473

474 Limited information is available about how far intensification can be taken without too
475 many internal and external detrimental effects. System internal trade-offs look at how
476 limited resources (e.g. land, labour, crop residues, cash) can be allocated across crop
477 and livestock production (and off farm activities), and thereby provide information on how

478 far current systems can intensify. The crop residue for fodder versus for soil amendment
479 debate has been quite intensive given the push for conservation agriculture (e.g. Giller *et*
480 *al.*, 2009; Valbuena *et al.*, 2012). For example, work by Rusinamhodze *et al.* (2013)
481 showed that the crop residue fodder versus soil amendment trade-off is not strong, and
482 that in central Zimbabwe about 25-50% of the crop residues can be returned to the soil
483 without having negative effects on cattle productivity. This would be enough to ensure
484 good soil cover, and limit soil erosion. However, despite the need for these trade-off
485 analyses (e.g. Klapwijk *et al.*, 2014) few other studies are available that explore these
486 internal, resource constraint driven, trade-offs. Externally, performance indicator-driven
487 trade-off analyses are even less available beyond studies that show that trade-offs exist
488 between production intensification and for example GHG emissions. Typically, in the low
489 input systems of many low income countries there is a large scope to improve emission
490 intensities (i.e. the GHG emission per unit of livestock product produced) while
491 intensifying production, but it is unclear in many systems up to what level production can
492 be increased while still reducing emission intensity. In absolute emission terms
493 investment in increasing the productivity of the existing cattle herd is attractive, as the
494 animals are already there and emissions already take place. Improved feeding of these
495 cattle will increase absolute amount of emissions (e.g. Herrero *et al.*, 2013) but not at the
496 same levels that it would take to achieve similar levels of improved total production
497 through expansion of a low productivity herd. Work by Amole *et al.* (2017) and Rufino *et*
498 *al.* (2009) has shown that large production increases can be achieved by relatively small
499 changes in livestock diets. Also the low productivity of the grasslands in many agro-
500 pastoral regions (e.g. Rufino *et al.*, 2011) gives ample opportunity to increase livestock

501 production (for example through agroforestry, incorporation of legumes or other better
502 regulation of the access to land use to avoid overgrazing). Given the fact that demand for
503 livestock products will rise sharply over the coming decades, this information is essential
504 to determine where investments in livestock products can be both efficient without further
505 major negative environmental effects.

506

507 **Conclusion**

508

509 This paper on the role of herbivores in sustainable agriculture in sub-Saharan Africa has
510 highlighted the beneficial aspects of integrating of livestock into the continent's farming
511 systems as well as the environmental consequences. Livestock are critical to the
512 livelihoods of rural populations in sub-Saharan Africa and essential to address agricultural
513 sustainability on the continent. Livestock deliver many “goods” in smallholder farming
514 systems in Africa including improving food and nutrition security, increased recycling of
515 organic matter and nutrients and the associated soil fertility amendments, adding value
516 to crop residues by turning them into nutrient-rich foods, income generation and animal
517 traction. Therefore, the over-emphasis on the negative consequences of livestock on the
518 environment as a result of inappropriate extrapolations based on livestock production
519 conditions in industrialized animal production systems is rather simplistic and should be
520 moderated by the narratives on the enormous importance of livestock in generating food
521 security for some of the more vulnerable people in the world and other “goods” in
522 smallholder mixed crop and livestock systems in SSA. To enhance agricultural
523 sustainability in SSA, the challenge is to optimize livestock’s roles in the farming systems
524 by maximizing livestock “goods” while minimizing the “bads”. This can be through better

525 integration of livestock into the farming systems, efficient nutrient management systems,
526 and provision of necessary policy and institutional support.

527

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534

535 **Declaration of interest**

536 The authors declare that they have no conflict of interest

537

538 **Ethics committee**

539 Not applicable

540

541 **Software and data repository resources**

542 None of the data were deposited in an official repository

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692 **Table 1** Key livestock production systems in sub-Saharan Africa

System	Agro-ecological zone	Rainfall (mm)	Length of Growing Period (day)	Dominant animal species	Dominant crop
Pastoral	Hyper arid, arid	<400	0 – 75	Cattle, sheep, goat, camel	-
Agro-pastoral	Arid, semi-arid	400 – 600	75 – 90	Cattle, sheep, goat	Sorghum, millet
Mixed crop-livestock	Semi-arid	500 – 800	90 – 180	Cattle, sheep, goat, pig, poultry	Maize, sorghum, millet
	Sub-humid	800 – 1 500	180 – 270	Cattle, sheep, goat, pig, poultry	Roots/tubers, maize
	Humid	>1 500	>270	Sheep, Goat, Pig, poultry	Roots/tubers
Peri-urban	Highland			Cattle, sheep, goat	Wheat, potato, teff
	Semi-arid, sub-humid		75 - 180	Cattle, sheep, goat, Poultry	Maize

693 Adapted from Otte and Chilonda (2002)

Table 2 Benefits and constraints of some intensification practices in smallholder mixed crop-livestock systems in sub-Saharan Africa

Practice	Benefit	Constraints	Extent of adoption	Reference
Fertilizer application	-Improve soil nutrient -increase crop productivity	-Unaffordable to many smallholder farmers -Difficult for rural farmers to access -Ineffective in absence of sufficient organic matter	-Widely used but at low rates	Pretty <i>et al.</i> , 2011; Sheahan and Barrett, 2017
Application of animal manure	-Improve soil nutrients, soil organic matter -Improve water infiltration capacity -Improve nutrient cycling in the system -Increased grain yield	-Inadequate quantity due to low number of animals -Lack of means of transport -Labour to apply the manure -Stealing of corralled animals -Other competitive use of manure -GHG emission	Widely practiced but at low rate due to inadequate quantity	Vall <i>et al.</i> , 2017; NRC, 2010
Use of improved crop varieties	-Higher grain yield -Higher fodder biomass for livestock -Climate smart	-High cost -Low availability due to weak seed systems	-Generally low except for improved dual purpose leguminous crops such as cowpea	Pretty <i>et al.</i> , 2011; Sheahan and Barrett, 2017

		-May not be locally preferred		
Water conservation techniques (zai, stone row, half-moon etc)	-Reduce runoff, collect water and nutrients -Reduces erosion -Rehabilitation of degraded land	-High labour demand	-Highly localized in the dryland areas	Rockström <i>et al.</i> , 2002; Douxchamps <i>et al.</i> , 2014.
Conservation agriculture	-Increase grain yield -Maximize nutrient retention in the system -Reduce water runoff and water-caused erosion	-Competitive use of crop residues as animal feed -Weed and pest control	-Generally low adoption	Rudel <i>et al.</i> , 2016; Baudron <i>et al.</i> , 2014.
Improved livestock breeds	-Higher productivity -Efficient nutrient use -Reduce GHG emission per unit of production	-Lack of artificial insemination -Availability of improved breed well adapted to the environment -High feed requirements -Multiple production objectives -Disease risk	-Generally low adoption except in peri-urban dairy production systems	Anderson, 2003; Pretty <i>et al.</i> , 2011.

Fodder production	<ul style="list-style-type: none"> -High biomass production -High nutritional value -Improved animal production 	<ul style="list-style-type: none"> -Availability of seed or seedling -Lack of technical capacity -Economic viability 	<ul style="list-style-type: none"> -Generally low except in peri-urban dairy production systems 	Pretty et al., 2011; Herrero et al., 2013.
Composting	<ul style="list-style-type: none"> -Increase soil carbon and soil organic matter -Increase nutrient availability -Increase crop yield -Improve soil moisture retention and water infiltration 	<ul style="list-style-type: none"> -High labour demand -Difficulty in transport -Can lead to significant loss of ammonia, CH₄ and N₂O to the atmosphere 	<ul style="list-style-type: none"> -Widely adopted in dryland areas 	Kabore et al., 2010; NRC, 2010.
Small scale mechanization	<ul style="list-style-type: none"> -Increased productivity -Reduced drudgery 	<ul style="list-style-type: none"> -High cost of farm machinery 	<ul style="list-style-type: none"> -Widely adopted at low level due to high cost 	Diao et al., 2014; Sheahan & Barrett, 2017.
Animal traction	<ul style="list-style-type: none"> -Increased productivity -Reduced drudgery 	<ul style="list-style-type: none"> -Lack of bull/oxen -Feed requirements of bull/oxen 	<ul style="list-style-type: none"> -Widely practiced but often limited to cash crops such as cotton. 	Savadogo et al., 1998; Sheahan & Barrett, 2017.

Table 3 *Dry matter, nitrogen and phosphorus balance of different land use types in Fakara, south-western Niger in 1998*

Land use type	%area of village land	Dry matter (kg ha ⁻¹ yr ⁻¹)	Nitrogen (kg ha ⁻¹ yr ⁻¹)	Phosphorus (kg ha ⁻¹ yr ⁻¹)
Rangeland	13.2	-135	-3.7	-0.23
Fallow	25.0	-112	-2.9	-0.10
Unmanured crop field	53.9	-126	-2.4	-0.13
Manured crop field	7.9	400	7.7	1.09

Adapted from Hiernaux and Ayantunde, 2004. Only manured field had a positive nutrient balance but only 10% of the crop field in the study site is manured

Figure caption

Figure 1 Perceived impact of intensification practices on household food security in Burkina Faso (n=400 households interviewed in Seno and Yatenga provinces)

Figure 2 Vulnerability of different families to food shortage (normalized ranks 0 to 1) in West Africa (data from survey of 550 households in Burkina Faso, Mali, Niger and Nigeria). Poor in livestock means those with no cattle and less than 5 sheep and goat. Those that lack cultivable land are those who lack access to land often immigrants.

Figure 3 Relative contribution of six livelihood sources to food security. Results reported by household food security groupings and by site, Yatenga, Burkina Faso (BF); Borana, Ethiopia (ET); Nyando and Wote, Kenya (KE). Column widths denote the relative household membership within each food security category at each site (after Ritzema et al., 2017). FAI is Food Availability Index while Household FAI groupings are expressed in MJ/MAE (Male Adult Equivalent) / day

Figure 4 Contribution of crop residues to household livestock (cattle, sheep and goat) diet across agro-ecological zones in West Africa

Figure 5 Historical changes in feed sourcing across the pastoral to highland gradient in Ethiopia, 30-40 years ago compared to present (2011) (adapted from Mekasha et al., 2014).

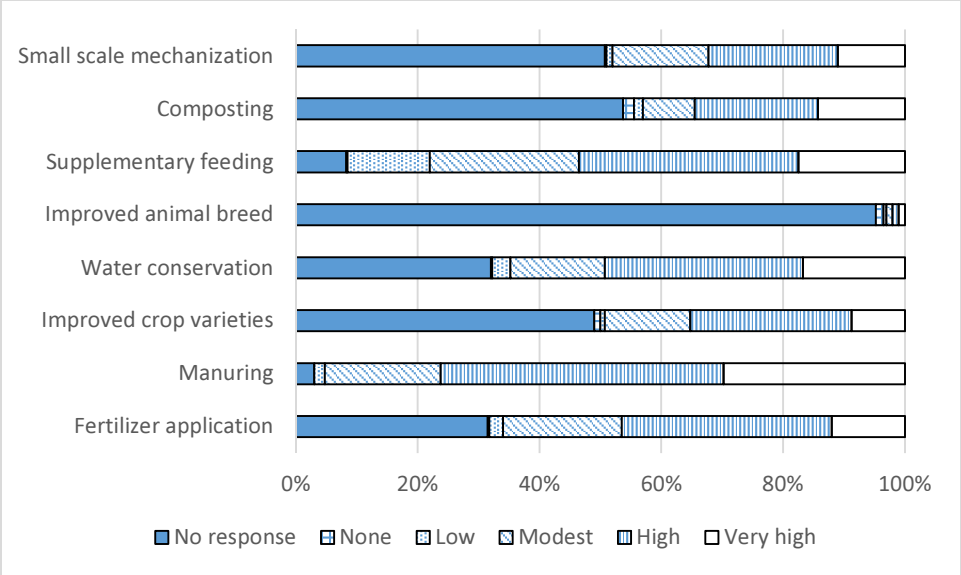


Figure 1

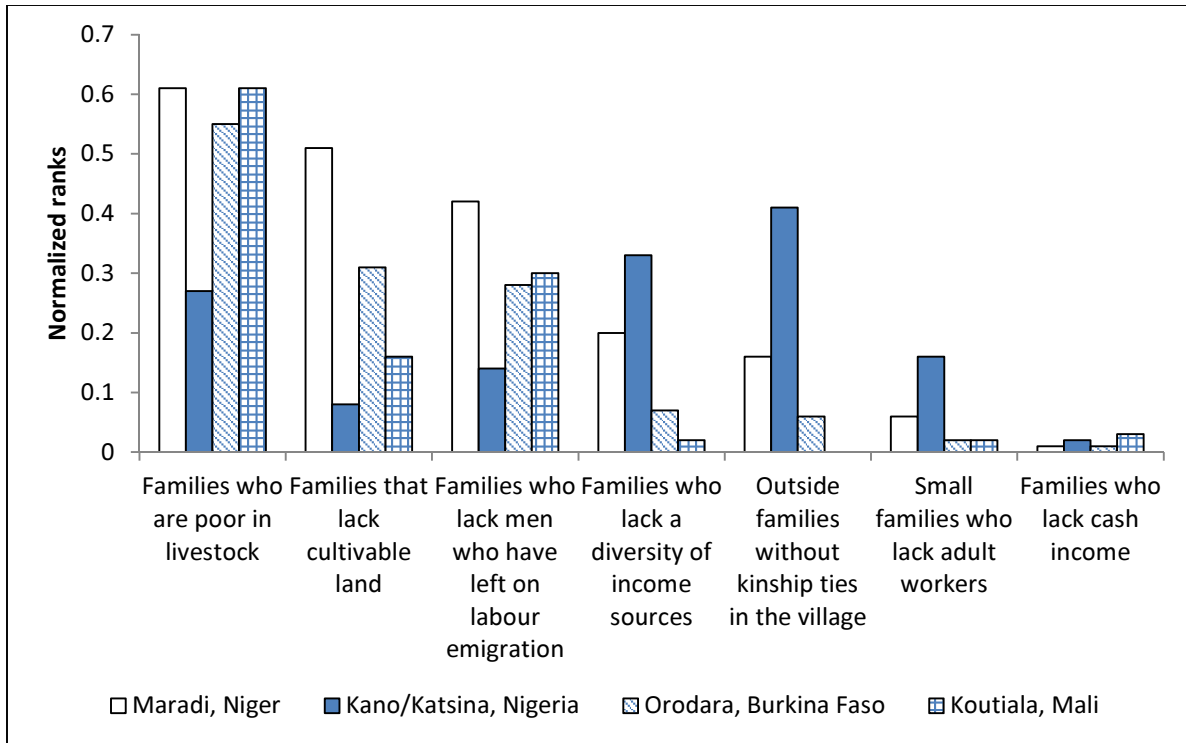


Figure 2

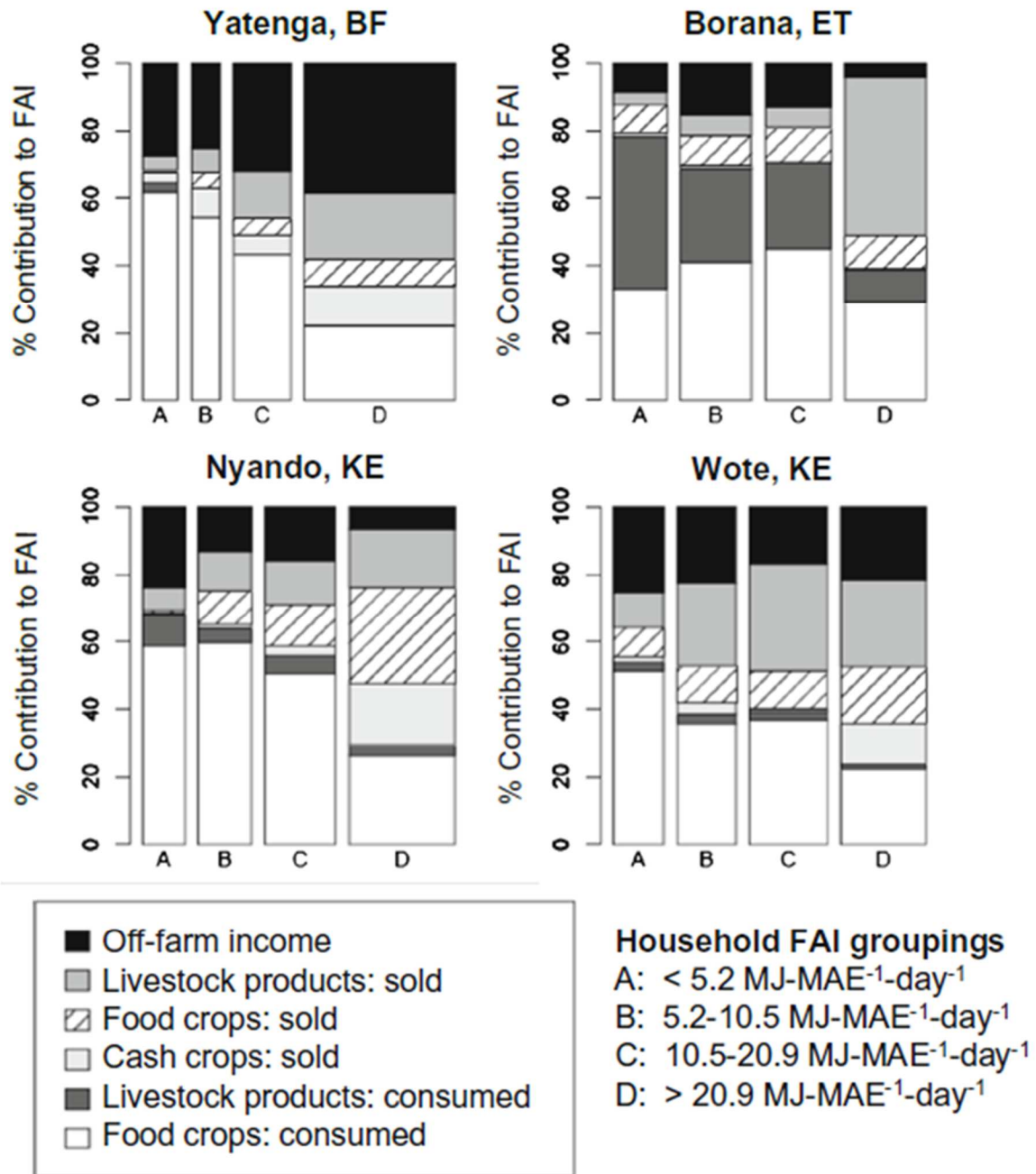


Figure 3

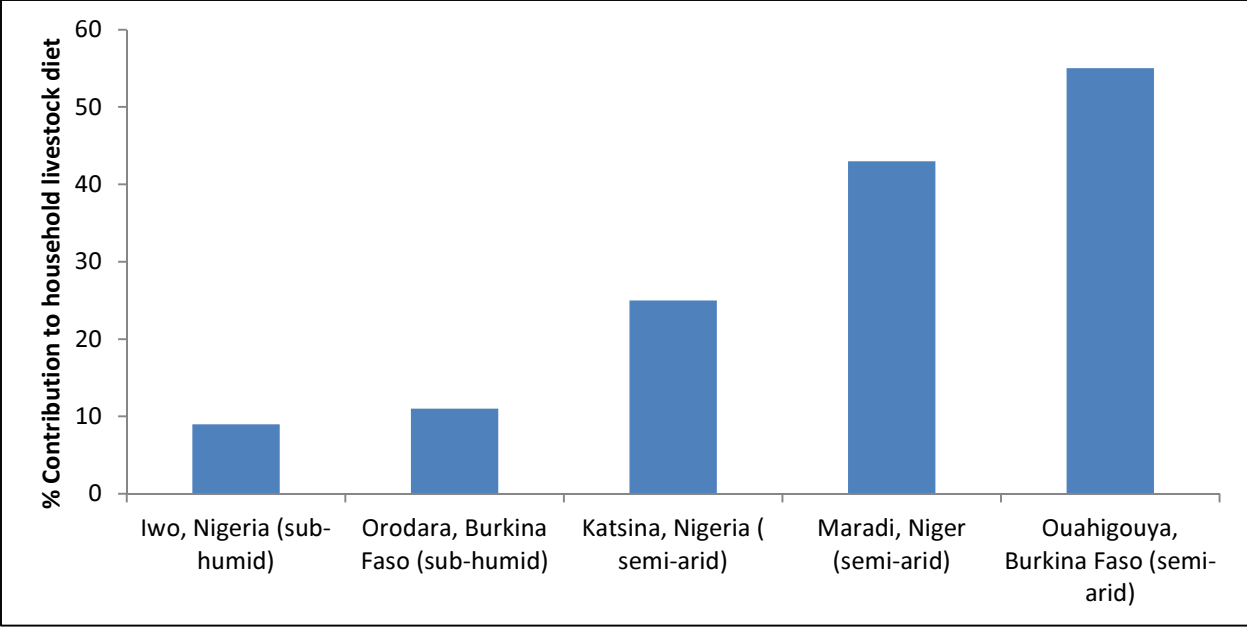


Figure 4

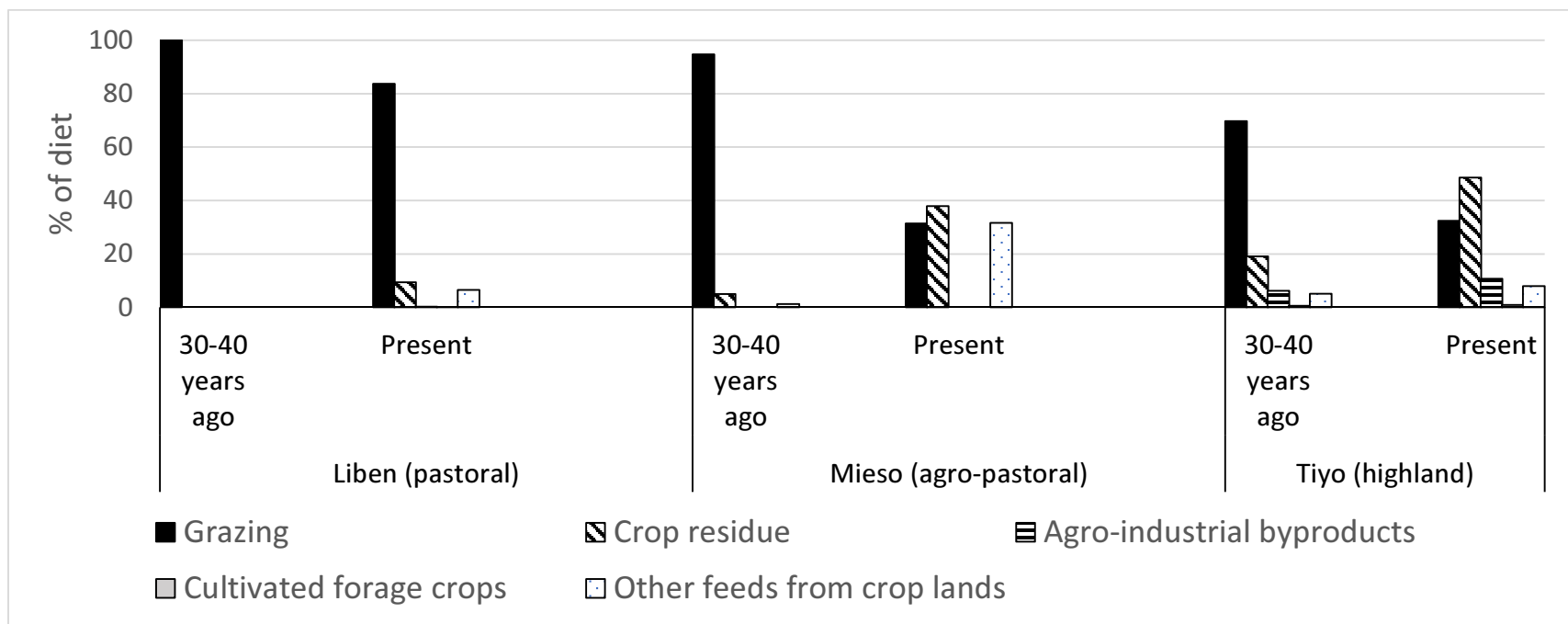


Figure 5