Farm-Level Impacts of Greenhouse Gas Reductions for the Predominant Production Systems in Northern Nigeria

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Abstract

This chapter summarizes the sources of greenhouse gas (GHG) emissions from different economic sectors in Nigeria and emphasizes those arising from agriculture and forestry. The impacts of climate change on agricultural systems in

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Nigeria are likely to be large, motivating the need for additional knowledge to assess current practices and formulate appropriate modifications for both mitigation and adaptation. Some current farming practices are believed to be adaptive, but further study would provide better assessments. We also analyzed the trade-offs between household income and GHG emissions at two contrasting sites in northern Nigeria. A farm optimization model maximizing the value of crop, livestock, and tree production activities in a single representative year assessed the potential impacts for GHG reductions of 10% and 25% and the maximum allowable reductions of 26% and 30% on farm activities and income. Emissions reductions of 10% reduced annual household incomes by less than 5% but required substantive changes, especially in livestock owned. Maximum possible GHG emissions reductions (while still meeting minimum household consumption needs) would require marked changes in production pattern and would lower household incomes by 22–44%. We did not assess effects over longer periods, where the role of livestock as a key asset may imply additional negative impacts. Productivity-enhancing technologies that would simultaneously reduce GHG emissions and increase incomes are needed for smallholder farms to play a larger role in climate change mitigation without the burden of reduced incomes and greater risk. This suggests the need for programmatic and policy actions both by national agricultural research systems and the Consultative Group for International Agricultural Research (CGIAR).

Keywords

Climate change · Agriculture · Nigeria

Introduction

Agriculture is the major employer of labor in Nigeria (Hansen et al. 2017) for over 70% of the estimated 200 million inhabitants (United Nations Department of Economic and Social Affairs: Population Division 2020). Almost 80% of over 70 million hectares of Nigerian land areas are under rainfed agricultural production that translates to about 40% of national Gross Domestic Product (GDP) (World Bank 2020). Agriculture is also a major contributor to greenhouse gas (GHG) emissions, as described below.

Overview of Greenhouse Gas Emissions from Agriculture in Nigeria

Agriculture was the largest of the four major sectors that contributed to Nigeria's GHG emissions in 2015. Agriculture, Forestry, and Other Land Use (AFOLU) accounted for two-thirds of total net national emissions of Teratonnes (Tt) CO₂ equivalent (CO₂-eq). The AFOLU sector includes emissions from land use,

livestock, and removals from harvested wood products. Land use accounted for an estimated 421 Tt CO₂-eq, or about 90% of emissions from AFOLU. One principal source of land-use emissions is methane (CH₄) and nitrous oxide (N₂O) from burning of rice, maize, sugarcane, and wheat residue biomass. Other sources include direct and indirect emissions of N₂O from nitrogen-based synthetic fertilizers used in managed soils, indirect emissions of N₂O from manure management, and direct CH₄ emissions from rice cultivation. For livestock, enteric fermentation and manure management for cattle, sheep, and goats contributed 29 Tt CO₂-eq, with the remaining amounts from camels, mules, swine, and horses. Enteric fermentation was 90% of total livestock-related emissions, with the remainder from paddock, range, and pasture and solid storage systems of manure management. N₂O and methane CH₄ were the most important GHG from manure management.

Total GHG emissions continue to increase. In 2019, the United States Aid for International Development (USAID) reported a 25% increase of 98 Mt. CO₂-eq in the country's overall GHG emissions from 1990 to 2014. The average annual change in total emissions was 1% and was mainly from the land-use change and forestry (LUCF) sector. Similarly, a trend assessment from the period 2000 to 2015 showed that AFOLU remained the highest emitter of GHG throughout the years under review (Federal Republic of Nigeria 2018). Emission from land-use category, forest land remaining forest land remained the principal source, and it increased by 25% during the period, whereas removals through HWP declined by 28%. There was an estimated 37% increase in emissions from rice cultivation, livestock production, manure management, and nitrogen-based synthetic fertilizers in managed soils over the entire period. The increase was attributed to the increase in livestock populations and more utilization of nitrogen-based synthetic fertilizers in managed soils as well as forest biomass loss. Thus, Nigeria's emissions are projected to grow to around 900 million tons per year in 2030, which translates to around 3.4 tons per person (Change Climate Response Policy 2015).

Impacts of Climate Change on Agriculture in Nigeria

Changes in climate, in particular, the frequency or severity of extreme events, are likely to have serious implications for rainfed agricultural production. Given the diversified socioeconomic conditions of agriculture in Nigeria, climate change could affect crop yields, disease patterns, and compound ecological disasters that include quelea bird's invasion, floods, and drought (Ajetomobi et al. 2015). However, the impacts are likely to vary by region. A vulnerability analysis conducted in 2014 by Nigerian's Federal Ministry of Environment indicated that states in the north experience higher degrees of vulnerability to climate change than those in the south (Haider 2019).

Many crops are sensitive to the modest changes in rainfall and temperature (Haider 2019). For example, the annual mean temperature needed for photosynthesis and growth is about 29 °C for maize and soybean. Currently, mean annual temperatures ranges from 30 °C to 34 °C. A mean annual temperature of 33 °C is desirable

for cotton, and temperature above this threshold can be harmful to plant development (Ajetomobi et al. 2015). The combination of increasing temperature and lower rainfall has hastened desert encroachment, with loss of the wetlands, and rapid reductions in the amount of surface water, flora, and fauna resources on land. Kebbi and Jigawa states observed 5–10% reductions in millet yields due to *Quelea* bird invasion, in addition to drought in Katsina, whereas Sokoto, Zamfara, Kaduna, and Kano states reported between 10% and 25% loss in groundnut yield from heavy floods (National Agricultural Extension and Research Liaison Services (NAERLS) & Planning Research and Statistic Department (PRSD), 2012). Rainfall intensity and distribution have been altered from the usual 500–1000 mm per year. Flooding in 2012 resulted in 363 deaths, massive economic loss, and the displacement of more than 3.8 million people. The total value of destroyed physical and durable assets was reported to be 1.48 trillion (US\$9.5 billion) or about 2% of the rebased GDP of US\$510 billion (Change Climate Response Policy 2015).

Under the business-as-usual scenario of the Change Climate Response Policy (2015), Nigerian agricultural productivity could decline by up to 50% by 2080, with reductions in GDP as large as 4.5% even by 2050. Consequently, in the absence of mitigating measures, there would be steady depletion of vegetation and grazing resources in affected regions. This could also prompt massive emigration and resettlement of people to areas less threatened by desertification. Subsequently, exacerbating communal clashes among herdsmen and farmers and inter-ethnic clashes (Haider 2019).

Adaptation and Mitigation Strategies for Nigerian Agriculture

Climate change mitigation is the improvement of agricultural production practices to reduce GHG emission, while adaptation involves the uptake of agricultural practices to be more suitable for a modified climate in a particular location (IPCC 2007). Nigeria is now implementing the reduction of emissions due to deforestation and forest degradation (REDD) (USAID 2019), through the national community-based forest resources management program. Other mitigations and adaptation strategies include the adoption of climate-adapted crops (e.g., drought-tolerant and early maturing varieties of crops) and in the livestock sector, improved feed, pasture, ranch, and paddock management systems (Change Climate Response Policy 2015). Programs are also being implemented to reduce the volume of irrigation water, while making more effective use of rainwater and groundwater. Other efforts are directed at providing early-warning seasonal climate forecasts to facilitate adaptation in a given growing season.

However, such adaptation and mitigation strategies are location- and context-specific and are described as autonomous or opportunist adaptation (Haider 2019). Planned adaptation strategies require additional knowledge about appropriate levels of inputs, tillage practices, and assessment of the future environmental conditions (e.g., rainfall, temperature, and relative humidity). Research to assess and implement actions for both adaptation and mitigation. Simulation modeling can support

assessment of adaptation strategies, particularly when experimental data are limiting and future environmental conditions uncertain (Nicholson et al. 2011; Kopainsky and Nicholson 2015). Consistent with the ongoing need for site-specific quantitative studies, the remainder of this chapter describes the use of modeling to assess the impacts of potential mitigation strategies on smallholder farming systems in the Northwestern area of Nigeria (Ayinde 2019).

Farm-Level Impacts of GHG Emissions Mitigation Strategies in Sudano-Sahelian and Sudan Savanna Ecological Zones in Northwestern Nigeria

An important question concerns the trade-offs among agricultural production, household incomes, and environmental impacts. To date, there are few studies that examine what actions would be required to reduce GHG emissions from smallholder agriculture production systems, and to understand the implications for household well-being. Northwestern Nigeria provides a conducive context for quantitative assessment of farm-level GHG mitigation strategies because it is a highly degraded region with higher degrees of vulnerability to climate change (Haider 2019). Within this region, differences in agro-ecology and production systems necessitate separate assessment of GHG-reduction strategies. Ayinde (2019) thus explored the production practices at two sites, the Bunkure (Sudan Savanna ecology) and Maigateri (Sudano-Sahelian ecology) local government areas (LGAs) located in Kano and Jigawa States, respectively (Fig. 1). The objective of the analysis was to describe predominant farming systems and discuss the extent to which they are consistent with either adaptation or mitigation strategies, and to evaluate quantitatively the impacts on agricultural production and potential trade-offs between household revenue and GHG emissions.

Kano and Jigawa differ in multiple respects, which facilitates a comparative analysis of mitigation strategies at the farm level. Kano is the most-extensively irrigated state in the country for the cultivation of rice, sugarcane, and vegetables, which are important emitters of GHG (IPCC 2013; Dunkelberg et al. 2014). Jigawa is characterized by shorter rainfall duration that does not support irrigated farming but sustains hardier shrubs and trees. In the LGAs of both states, however, mixed farming of grain and legume crops, trees, and livestock keeping are practiced.

Ayinde (2019) used participatory rural appraisal (PRA) and key informant interviews to characterize existing production systems at both study sites. Data were collected on the economic and environmental performance of the predominant production systems, land preparation, retaining of trees on crop field, use of trees branches and stem for firewood, use of crop residue as mulch, modified planting dates, use of early maturing crop variety, and agrosilvopastoral system. Emphasis were on trees that could serve multiple purposes of dry season feed, enriching soil Nitrogen, increasing protein and energy content in fodder while mitigating GHG emissions. This information was necessary to assess whether the production practices employed aligned with either a mitigation or adaptation strategy. The key

Fig. 1 Locations of the study sites Maigateri in Jigawa State and Bunkure in Kano State

informant interviews provided data of estimates of household-level expenditures on tree, crop, and livestock activities (See the assumed structure of inputs and outputs in the tree-crop-livestock production optimization model Appendix Table A1), the cost of animal draught, and the cost of manure applied. The description of the key specific

inputs used in the current production practices were necessary to estimate the GHGs emissions (CH₄, N₂O, CO₂, and non-CO₂) in Appendix Tables A2.1 and A2.2.

The emission factors (EF) used to estimate GHG emissions to specific farm activities were obtained from IPCC Tier 1 default equations as well as methods from Standard Assessment of Mitigation Potentials and Livelihoods in Smallholder System (SAMPLES; www.samples.ccafs.cgiar.org) that corresponds to the predominant production systems in the study region. Data on dry matter (DM), metabolizable energy (ME), and crude protein (CP) that corresponded to the tree and crop yield levels were obtained from secondary sources such as feed composition tables or journal articles and grey literature including Feedipedia; FAO source: (<http://www.fao.org/ag/againfo/themes/documents/PUB6/P620.htm>); and (Dupriez and De Leener 1998).

To assess the potential impacts on agricultural production patterns and full household income scenarios evaluated a baseline (current practices and emission levels) and required GHG reductions of 10%, 25%, and the maximum reductions consistent with meeting assumed household consumption needs (26% and 30% reductions compared to the baseline). See the detailed description of the optimization model used to assess trade-offs between household welfare (income) and farm-level GHG emissions in Appendix 1.

Current Production Practices as Adaptation or Mitigation Strategies

A key finding was that farmers were aware of the multiple uses and economic value of trees for wood, food, fuel, fodder, soil protection, and soil reclamation (Table 1),

Table 1 Tree and crop (cereal and legume) production practices reported by households in Bunkure and Maigateri

Crop type and production practice	Bunkure		Maigateri	
	N = 50		N = 55	
	Frequency	Percentage	Frequency	Percentage
Trees				
Retained trees on crop field	50	100	55	100
Firewood	19	38	11	20
Cereal				
Predominant cereal grown	26	52	29	53
Use of improved sorghum varieties	11	22	16	29
Construction	13	26	14	25
Fuel	11	22	11	20
Legume				
Predominant legume grown	30	60	29	53
Sell	45	90	42	76
Fodder to own livestock	4	8	10	18
Soil amendment	1	2	3	6

similar to previous studies (Change Climate Response Policy 2015; UN-REDD Programme 2015). Consequently, not all trees were lopped on crop fields. For instance, 30% and 44% of farmers in Bunkure and Maigateri LGAs, respectively, predominantly allowed their Neem (*Azadirachta indica*) trees to remain on the crop fields validating the finding of (Bayala et al. 2011). About 36% (Bunkure) and 42% (Maigateri) of farmers sowed some selected trees that are used mainly as live fences around their farms with 38% of its biomass mostly used as fuel in Bunkure LGA and 31% as manure in Maigateri LGA.

Furthermore, of all the trees allowed to remain on the farm, none met the criteria for the study (i.e., dry season feed, enriching soil nitrogen, increasing protein and energy content in fodder while mitigating GHG emissions like Locust-beans (*Parkia biglobosa*), Camel's foot/*Kalgo* (*Piliostigma reticulatum*) and are distinctively the most popular leguminous tree owned by 10% in Bunkure LGA and 24% of farmers in Maigateri LGA. Personal conversation with staff members of the outstation office of Forestry Research Institute of Nigeria (FRIN), in Samaru (Zaria, Kaduna State) revealed that Locust-beans/*Dorowa* (*Parkia biglobosa*), *Kalgo* (*Piliostigma reticulatum*), and *Gawo* (*Acacia albida*) trees were generally not planted because their seedlings or seeds were undomesticated thus, virtually unavailable. It is further compounded by the long period of growth (Bayala et al. 2014). However, efforts of FRIN were said to be underway to ensure the availability of Locust-beans (*Parkia biglobosa*) seeds or seedlings for propagation with growth period under 7 years as against the natural one of between 12 to 15 years.

Sorghum was the predominant cereal grown by over 50% of farmers in the two study locations. Most farmers in both LGAs (50% and 53%), reported that their sorghum residues comprised an adaptation plan for dry season supplementary feed/feed reserve for their ruminant livestock. About 60% of farmers in Bunkure LGA cultivated Soybean while, 53% in Maigateri LGA cultivated groundnut as their predominant legumes. Despite the numerous benefits of soybean and groundnut residue biomass for nitrogen fixation and GHG mitigation when used for soil amendments as an adaptation strategy, majority of farmers in Bunkure and Maigateri LGA sold their crop residue biomass. The implication of these practices are consequential as it may lead to more emissions of CH₄, CO₂, and N₂O, which may result in accelerated nutrient depletion from burning of bushes and crop residues, leaching, and acid rains (NH₃ volatilization) from the application of inorganic fertilizer (IPCC 2013). Once there is accelerated nutrient depletion, there may be gross production declines.

Farmers in the study zones claimed that unplanned consumption by free ranging livestock reduced the incentives for use of crop residues soil amendments. Therefore, except by-laws and community conventions are in place to restrict free grazing, the use of biomass for soil amendment faces constraints for the poorly sourced farmers of Bunkure and Maigateri LGAs, who would rather sell their crop residue than have them consumed by free-ranging livestock.

Adaptation strategies such as change in sowing dates and use of early maturing varieties were adopted by most farmers in the regions. However, such practices in addition to mulching are merely coping/autonomous or opportunist strategies by

Table 2 Livestock production reported by households in Bunkure and Maigateri

Livestock characteristic	Bunkure		Maigateri	
	N = 50		N = 55	
	Frequency	Percentage	Frequency	Percentage
Livestock				
Predominant breed of sheep	25	50	30	55
Predominant breed of goat	32	64	40	73
Seasonal tethering/cut and carry	19	38	15	37
Intensive/peri-urban ruminant husbandry	1	2	1	2

farmers as described by Haider (Haider 2019). More is required of these practices in terms of investment in infrastructure, subsidies, research, innovation, and tax regimes to attain planned adaptation strategies.

Livestock production is a major activity among smallholder farmers in Bunkure and Maigateri, LGAs. During the focus group discussions, farmers reported that most crops were sold immediately after harvest. Revenues from crop sales were used to purchase animals, particularly ruminant livestock. The Red Bororo (100%) is the major breed of cow in Maigateri LGA, whereas Sokoto Gudali is reared by 60% of farmers in Bunkure LGA (Table 2). A cow, 5 sheep, and 6 goats are the average herd size of cattle, sheep (Uda), and goats (Red Sokoto or Maradi Breed) owned per household in Bunkure. Households in Maigateri owned an average of 2 cows, 12 sheep, and 14 goats. Livestock is fattened for up to 7 months and then sold. Part of the revenues generated from livestock sales is used to acquire farm inputs for another planting season.

Farmers in Bunkure and Maigateri LGAs believe a successful adaptation strategy is “compound dairy” (a traditional system of milking in which animals are confined to the compound rather than allowed to graze). The cows supply the family with fluid milk for consumption and any excess above household needs is sold or processed into other dairy products. In this system, dairy animals were either tethered and fed on traditional cut and carry using cereal/legume crop residue or allowed to graze freely around the compounds in the day and confined in the night in the wet season. It was the most widely practiced adaptation mechanism among all households as confirmed by 98% of households.

A key issue with the compound dairy is whether it is possible to achieve higher productivity per animal from increased grain cultivation, without increasing GHG emissions. The use of concentrates or cultivation of pastures for supplementary feeding of indigenous Zebu and Ndama breeds of cattle is uneconomical and of doubtful feasibility (Ayantunde et al. 2007). Because, there is no strong evidence of economies of scale, due to under-utilized family labor and the ability of ruminants to exploit low-value roughage, including that gathered or grazed from public lands (Mcdermott et al. 2010). Moreover, higher-productivity breeds cannot generally replace indigenous Zebu and Ndama breeds of cattle, as these breeds are not suitable for North-western Nigeria (Ayantunde et al. 2011). Although studies confirm

Table 3 Optimal farm-level tree-crop-livestock production decisions for the three scenarios in Bunkure and Maigateri LGA

Outcome or activity	Units	Bunkure				Maigateri			
		Baseline	Difference with – 10% GHG reduction	Difference with – 25% GHG reduction	Maximum GHG reduction	Baseline	Difference with – 10% GHG reduction	Difference with – 25% GHG reduction	Maximum GHG reduction
Tree									
Locust beans/ Camel's foot	Ha	2	0	–0	–1	2	0	0	0
Crop									
Sorghum	Ha	1	0	0	0	1	0	0	0
Soybean/ groundnut	Ha	0	0	0	0	3	0	–0	–2
Animals									
Cow	Head	0	0	0	0	1	–0	–1	–1
Sheep	Head	10	–5	–5	–5	5	–1	–1	–1
Goats	Head	5	0	0	0	4	0	0	0
GHG emissions per farm	Kg CO ₂ eq /yr	2943	2649	2207	2175	3057	2751	2293	2124
Revenues									
Locust beans/ Camel's foot	000 ₦/ yr	2316	0	–4746	–6754	8606	0	0	0
Sorghum	000 ₦/ yr	8334	0	0	0	7430	0	0	0
Soybean/ groundnut	000 ₦/ yr	3004	0	0	0	1105	0	–1606	–6051

Cow	000 ₦/ yr	7226	7723	0	0	1983	-2937	-1145	-1145
Sheep	000 ₦/ yr	2191	-1071	-1061	-1061	7385	-1955	-1955	-1955
Goats	000 ₦/ yr	1230	0	0	0	6165	0	0	0
Cost of purchased inputs									
Locust beans/ Carnel's foot	000 ₦/ yr	1722	0	-3529	-5022	6002	0	0	0
Sorghum	000 ₦/ yr	3493	0	0	0	1976	0	0	0
Soybean/ groundnut	000 ₦/ yr	218	0	0	0	2499	0	-3633	-1369

improved feeding and manual management system as mitigation strategies that reduce total emissions of CO₂, CH₄, and N₂O in the livestock sector, the extent to which this is possible requires further study to determine appropriate strategies for location-specific reductions.

Farm-Level Trade-Offs Between Income and GHG Emissions

GHG reductions of up to 26% were possible with assumed minimum levels of household consumption in Bunkure LGA (Table 3), but reduction would require reductions in farm-level revenue of more than 20%. Reductions were achieved essentially from reductions in the sales of sheep meat, locust bean pod, branch, and trunk in addition to a reduction in the sales of sheep manure (Appendix Table A3). Maximum possible decreases in GHG emissions require reduction of livestock to minimum assumed household consumption levels and a reduction in profitable locust bean production through reduction in land area by 29%. Similarly, quantities of purchased input used for locust bean production, reduced significantly for urea, seeds, and agricultural pesticides. Below 26%, the model could not attain feasible adaptation strategies because it could not meet household requirements as assumed.

In Maigateri LGA, GHG reductions of up to 30.5% could be attained with minimum levels of household consumption. However, such reductions in GHG emissions would require reductions in farm-level revenue of about 44%. Reductions in GHG emissions were accomplished primarily decreases in groundnut, cow, and sheep production and from up 100% reduction in the sales in the livestock component as well as 55.7% reduction in sales of groundnut grain in the crop component. Maximum GHG emissions reduction implied decreases in groundnut production, in addition to the reduction of livestock to minimum assumed household consumption levels.

By implication, the assessment of trade-offs that indicate potential pathways for increased agricultural productivity with fewer negative environmental effects, are usually location- and context-specific, thus difficult to generalize, categorize, and describe in contrasting socio-ecological contexts (e.g., Thornton et al. 2018). Yet, it could be futile to identify win–win production without a framework to generalize them into policy recommendations and developmental actions. The major contribution of this chapter is the establishment of a generic conceptual framework that can be used across farms of different agro-ecological zone. Particularly for comparative assessment and prioritization of policy options, that could be scaled up from local/community or farm level to regional or country levels.

However, better understanding of trade-offs is needed to attain win–win scenario (Steenwerth et al. 2014; Klapwijk et al. 2014; Kanter et al. 2016). More accurate indices and numbers could be achieved with the use of system dynamic model analyses (Stermann 1989; Kopainsky and Nicholson 2015), and could be considered as suggestion for further studies.

Conclusions

This chapter has documented the importance of agriculture and land use in the generation of GHG emissions in Nigeria, and the need for both adaptation and mitigation strategies in smallholder agriculture. The farm-level impacts provide information needed to formulate appropriate mitigation and adaptation strategies for going forward in climate-smart agriculture. A key finding from the farm-level analysis is that revenue generated decreases with GHG emissions mitigation and adaptation. Maximum possible GHG emissions reductions (while still meeting minimum household consumption needs) would require marked changes in production pattern and would lower household incomes. There appear to be no win-win adaptation strategies with current production practices and technologies that both increase revenue generation and reduce GHG. Productivity-enhancing technologies that would simultaneously reduce GHG emissions and increase revenue are needed for smallholder farms to play meaningful climate change mitigation and adaptation strategies in Nigeria without the burden of reduced incomes and greater risk. We also did not assess effects over longer periods, where the role of livestock as a key asset may imply additional negative impacts. This suggests the need for programmatic and policy actions to be taken by both national agricultural research systems and the Consultative Group for International Agricultural Research (CGIAR) to promote climate-smart agriculture in Nigeria.

Acknowledgments This study was conducted with the financial support of the Standard Assessment of Mitigation Potentials in Smallholder Farmers Livelihood System (SAMPLES), a CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS).

Appendix 1: Detailed Description of the Optimization Model Used to Assess Trade-Offs Between Household Welfare (Income) and Farm-Level GHG Emissions

The Farm-Level Optimization Model

The farm model (Eq. 1) assessed the potential trade-offs between GHG reductions and farm revenue with the aim to identify the impacts of possible mitigation strategies and facilitate future analysis of potential adaptation opportunities through production practices that result in both reduced emissions and increased farm incomes.

The objective function Z maximizes net household full revenue generated, given by:

$$Z = - \sum_{m=1}^{12} W_m \cdot X_m^L - \sum_{i=1, j=1}^{i=4, j=6} P_i \cdot X_{ij}^I + \sum_{j, p=1}^{20} C_{jp} \cdot X_{jp}^P \quad (1)$$

where

W_m = Wage paid per hour of hired labor in month m

X_m^L = Hours of labor hired by the household in month m

X_{ij}^I = Purchased input i for tree or crop production activity j

P_i = Price of purchased input i per unit

C_{jp} = Unit value per kg for subproduct p of tree, crop, or livestock activity j

X_{jp}^P = Production of subproduct p of tree, crop, or livestock activity j

The objective function maximizes the total value of products derived from activities $j = 1$ to 6 locust bean and camel's foot in Bunkure and Maigateri, respectively. Represented as tree species. Branches and trunk of the Locust bean and Camel's foot trees can be used to meet household firewood requirements. Sorghum, legumes species are predominantly soybean in Bunkure and groundnut in Maigateri. While livestock includes cows, goats, and sheep production. "Full income" is specified as sum of product sold by the household. In addition to the opportunity cost of product consumed by the household less the costs of hired labor and the value of purchased inputs $i = 1$ to 4 that include fertilizer (NPK mix and urea), agricultural chemicals, manure, and seed for grains and legumes. Each of the products has subproducts that are either sold to generate revenue or used as internally generated inputs (Table A3) or used as internally generated inputs on the farm (Table A1). A total of 20 (j, p) combinations of activities and subproducts are represented.

Land is one of the basic farm household resource constraint and the predominant land type (upland) used for rainfed production is modeled with the following equation:

$$L \geq \sum_{j=1}^6 L \cdot X_j^P \quad (2)$$

which shows that the total land available to the household, L , must be greater than or equal to total land used for annualized production activities j , X_j^P . Thus, for model simplification, the agricultural activities were assumed to be yearly. Land rental is excluded to avoid unbounded solutions.

A labor constraint signifies that the sum of household labor H_m and or hired labor, X_m^L available must exceed or meet total labor required for agricultural production activities, X_j^P

$$H_m + X_m^L \geq \sum_{j=1}^7 a_{jm}^L \cdot X_j^P \quad (3)$$

The purchase of inputs used for production activities is given by the product of the activity X_j^P and the fixed coefficient a_{ij}^I

$$a_{ij}^I \cdot X_j^P \leq X_{ij}^I \quad (4)$$

Inputs produced on-farm and used for other production include tree fodder, crop residue biomass, manure, and milk. Tree fodder and crop residues are used as animal feed or soil amendment. Tree components were partitioned using formula adapted from Powell et al. (1995) and Bayala et al. (2014). Residue obtained as by-product from sorghum production were derived, using formula for harvest index adapted from Powell et al. (1995). Similarly, manure is used as fertilizer, while milk is used to feed young livestock. Formula for calculating manure production was in line with Powell et al. (1995) and Ayantunde et al. (2000). The relationships are represented by this equation:

$$\sum_{j'} a_{j'j}^R \cdot X_{j'}^P \geq \sum_j a_{j,j}^R \cdot X_j^P \quad (5)$$

The equation above requires that the amount available from the sum of production of j' sources must be greater than or equal to the sum of farm-generated resource used. The model includes constraints for animal nutrient requirements: dry matter (DM, kg/day), crude protein (CP, g/day) and metabolizable energy (ME, in mega joules, MJ) FAO, http://www.fao.org/ag/againfo/themes/documents/PUB6/P6_20.htm: that states the recommended daily ME for maintenance of sheep and goat is 5.1 and for cow producing less than 5 lit per day is 46 ME MJ/day. Recommended daily CP and DM requirement is 3% animal body weight, with average weight of 350 kg cow, 20 kg sheep, and 20 kg goat translating to 400, 32, and 32 g CP/day, respectively

The constraint in equation 6 requires the diet fed to livestock must be less than or equal to the nutritional requirements for metabolizable energy (ME), crude protein (CP), and dry matter (DM) is represent thus:

$$\sum_{j',p} a_{j',p,n}^{NS} \cdot X_{j',p,j}^{USE} \forall j \in \text{animal}, (j', p) \in \text{feeds} \geq a_{j,n}^{NR} \cdot X_j^P \quad (6)$$

which indicates that the sum of the (j,p) the product of feeds allocated to animals of type j , $X_{j',p,j}^{USE}$ and the nutrient content of those feeds, $a_{j',p,n}^{NS}$, must exceed the required $n = 3$ nutrients for animals of type j , $a_{j,n}^{NR} \cdot X_j^P$

Products (j, p) allocated to household use $X_{j,p}^{HH}$, also must meet minimum household consumption requirement $HHR_{j,p}$, as follows:

$$HHR_{j,p} \leq X_{j,p}^{HH} \quad (7)$$

A balance constraint ensures that uses of products (j, p) for household consumption, sales, or use in production is less than or equal to the total sources supplied:

$$X_{j,p}^{HH} + X_{j,p}^{SALES} + \sum_j a_{j'j}^R \cdot X_j^P \leq a_{j,p}^{YLD} \cdot X_{j,p}^P \quad (8)$$

Table A1 Assumed structure of inputs and outputs in the tree-crop livestock production optimization model

Activity (j)	Inputs	Output	Saleable output	Consumed output
Locust bean and Camel's foot trees	Seeds, urea fertilizer, pesticides, labor, manure	Fodder, pod, pod valve, bran, branches, and trunk	Fodder, pod, pod-valve, bran	Pod, branches, and trunk
Sorghum	Seeds, urea, and NPK fertilizer, pesticides, labor, manure	Grain, fodder, bran	Fodder, bran	Grain
Soybean and groundnut	Seeds, urea, and NPK fertilizer, pesticides, labor, manure	Grain, fodder, bran, hull	Grain, fodder, bran, hull	Grain
Cow	Sorghum Stover/straw, Soyhull/groundnut residue biomass	Meat, milk, manure	Meat, milk, manure	Milk
Goat	Sorghum Stover/straw, Soyhull/groundnut residue biomass	Meat, manure	Meat, manure	Meat
Sheep	Sorghum Stover/straw, Soyhull/ groundnut residue biomass	Meat, manure	Meat, manure	Meat

An additional constraint requires that the sum of GHG emissions $a_j^{GHG}X_j^P$ generated in the predominant farm practices must equal total GHG emissions per farm:

$$\sum_{j=1}^6 a_j^{GHG}X_j^P = GHG \quad (9)$$

which is used in the specification of alternative scenarios about required GHG emissions reductions per farm. For simplicity, a_j^{GHG} does not include the effects of emissions from application of lime, pre-farm operations during storage, and transportation as well as all mechanized farm operations, as these are minimal in this farming system.

The Tier 1 default methods and emission-factors (EFs) from the 2006 version of the guidelines that considered management practices with soils containing N inputs (Table A2.1) was employed. The default Carbon (C) produced is less than the estimated C harvested, and dead wood and litter stocks present in the predominant production system are at equilibrium and specified as zero. The Tier 1 default EF of 0.20 representing 20% for CO (NH₂)₂ was assumed for calculating annual CO₂ emissions from urea application in kg C/yr. Amounts of CO₂ equivalents were calculated by multiplying CO₂–C emissions values obtained by 44/12. Non-CO₂ emissions due to fire were estimated from the product of land area, (hectare), mass of fuel available for combustion, (tons ha⁻¹), combustion factor values, and emission

Table A2.1 Assumed values of GHG emissions related to land use, Bunkure and Maigateri LGAs

Type of emissions	Bunkure		Maigateri			
	Locust bean (kg CO ₂ eq/ha/ year)	Sorghum (kg CO ₂ eq/ha/ year)	Soybean (kg CO ₂ eq/ha/ year)	Camel's foot (kg CO ₂ eq/ha/ year)	Sorghum (kg CO ₂ eq/ha/ year)	Groundnut (kg CO ₂ eq/ha/ year)
Non-CO ₂ from burning	127.5	127.5	127.5	127.5	127.5	127.5
Direct N ₂ O soils	10.1	142.3	12.3	6.6	146.4	11.4
Indirect N ₂ O soils	2.3	21.6	0.0	1.1	25.6	0.0
Urea application	36.7	73.3	0.0	18.3	32.1	18.3

Table A2.2 Assumed values of GHG emissions related to animal numbers, Bunkure and Maigateri LGAs

Type of emissions	Bunkure				Maigateri			
	Cows (kg CO ₂ eq/TLU/ year)	Sheep (kg CO ₂ eq/TLU/ year)	Goats (kg CO ₂ eq/TLU/ year)		Cows (kg CO ₂ eq/TLU/ year)	Sheep (kg CO ₂ eq/TLU/ year)	Goats (kg CO ₂ eq/TLU/ year)	
CH ₄ emissions	987.0	172.2	109.6		987.0	172.2	109.6	
N ₂ O emissions	186.7	20.8	24.4		186.7	20.8	24.4	

Table A3 Optimal farm-level tree-crop-livestock production decisions for the three scenarios in Bunkure and Maigateri LGA

Outcome or activity	Units	Bunkure			Maigateri				Maximum GHG reduction
		Baseline	Difference with – 10% GHG reduction	Difference with – 25% GHG reduction	Maximum GHG reduction	Baseline	Difference with – 10% GHG reduction	Difference with – 25% GHG reduction	
Sales of products	Kg/yr								
Tree									
Locust beans/Camel's foot pod		3383	0	–697	–993	1180	0	0	0
Locust beans/Camel's foot fodder		0	0	284	0	0	372	372	0
Locust beans/Camel's foot branch		3045	0	–1073	–1527	0	0	0	0
Locust beans/Camel's foot trunk		1361	0	–2790	–3970	4745	0	0	0
Crop									
Sorghum bran		0	0	66	0	0	31	31	0
Soybean/groundnut grain		0	0	0	0	2601	0	–385	0
Soybean bran/groundnut meal		0	0	3	0	0	13	11	0

(continued)

Table A3 (continued)

Outcome or activity	Units	Bunkure			Maigateri				
		Baseline	Difference with – 10% GHG reduction	Difference with – 25% GHG reduction	Maximum GHG reduction	Baseline	Difference with – 10% GHG reduction	Difference with – 25% GHG reduction	Maximum GHG reduction
Soyhull/groundnut haulms		1	0	0	0	0	104	804	0
Animals									
Cow meat		43	46	0	0	160	–24	–93	–93
Cow milk		0	146	0	0	187	–48	–187	–187
Cow manure		257	275	0	0	811	–120	–468	–468
Sheep meat		142	–131	–142	–142	36	–36	–36	–36
Sheep manure		983	–481	–521	–521	503	–133	–133	–133
Goat manure		555	0	0	0	432	0	0	0

factor (g kg^{-1} dry matter burnt) for various type of burning. The carbon dioxide equivalents (CO_2eq) factor was set at zero based on the assumption that the conversion of CO and NO_x has weak global warming potential.

N_2O emissions include volatilization and leaching from manure management system (MMS) and managed soil (MS). Other N_2O losses considered are annual amount of N in crop residues (above and below ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually, (kg N yr^{-1}). DAP composition for Nitrogen (N) content in 50 kg bag of NPK fertilizer with urea excluded is 0.20 kg N. All emissions were converted to N_2O by multiplying 44/28 with values obtained

In ruminant livestock production, MMS and enteric fermentation result in CH_4 emissions in (Table A2.2). The EFs for sheep, goat, and mature cow grazing on large areas in developing countries were used. One TLU represents 250 kg live weight; equivalent of 1 camel, 1.43 cattle, 10 sheep/goats according to Ayantunde et al. (2011). All results were converted to carbon-dioxide equivalents (CO_2eq). In accordance with IPCC, a unit of CO_2 , CH_4 , and N_2O represents 1, 21, and 310 units of CO_2eq , respectively

To implement scenarios requiring farms to reduce GHG emissions from current levels, an additional constraint was developed to ensure GHG emissions generated from the predominant production practice is less than the assumed amount:

$$\sum_{j=1}^6 a_j^{GHG} X_j^P \leq GHGLIM \quad (10)$$

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