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Income and greenhouse gas (GHG) emission trade-offs on smallholder farms at two sites in northern Nigeria

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Abstract

This study analyses the trade-offs between welfare (measured by income) and greenhouse gas (GHG) emissions using a farm-level optimisation model that incorporates the predominant cereal (sorghum), legumes (groundnut, soybeans), livestock (cattle, goats and sheep) and trees (locust bean, camel's foot) representative of production systems at two contrasting sites in northern Nigeria. The optimisation model maximises the value of total farm production, subject to constraints on GHG reductions of 10%, 25% and the maximum reductions that allow households to meet minimum consumption requirements. Substantive reductions in livestock and legume production would be required to achieve the maximum possible reductions from current emissions and would reduce household income by 22% and 44%, respectively. Under current production practices, reductions in GHG emissions reduce household income, which suggests the need for further research on productivity-enhancing technologies that could both enhance income and reduce GHG emissions in these production contexts.

Key words: income; greenhouse gas emissions; agriculture; smallholder; Nigeria

1. Introduction

Smallholder farm-level productivity in many lower-income country settings has not attained its full potential (National Agricultural Extension and Research Liaison Services & Planning Research and Statistic Department [NAERLS & PRSD] 2012) but smallholder farm-level production and processing contribute to greenhouse gas (GHG) emissions and climate-change (Campbell *et al*. 2014). Most previous literature linking agriculture and climate change has examined alternative mitigation strategies in higher-income countries (e.g. Eleto Torres *et al*. 2015; De Pinto *et al*. 2016) or examined how smallholder farms in lower-income countries might be affected by or cope with climate change (Bellarby *et al*. 2014). There are few empirical studies on trade-offs between farm-level GHG emissions and welfare (e.g. Paul *et al*. 2017) or on the potential productivity improvements required to avert trade-offs (Tittonell *et al*. 2015).

Northern Nigeria provides a conducive context to evaluate trade-offs between welfare and agricultural GHG emissions due to the importance of smallholder farmer production. It may be a potential "hot spot" for GHG emissions (Rufino *et al*. 2015) because it is the most degraded region in the country (Farauta *et al*. 2011), given the severity of the loss of soil fertility and subsequent low productivity (Maiangwa *et al*. 2007). Furthermore, the potential trade-offs of reducing GHG emissions on smallholder farms are often unknown (Nicholson *et al*. 2011; Thornton *et al*. 2018).

A key question is whether changes in smallholder farm-level production activities can reduce GHG emissions without negatively affecting household income. This research addresses this question for smallholder farms using crop–tree–livestock systems at two sites in northern Nigeria as case examples. The objective of this study was to assess trade-offs in reducing GHG emissions and income for two representative smallholder farms in northern Nigeria.

2. Materials and methods

This study developed farm-level linear optimisation models for each of two locations in northern Nigeria and used the models to assess the agricultural production patterns and full household income (value of goods produced, whether sold or not) with and without restrictions on GHG emissions. An optimisation model is appropriate in this case to assess the effects on income, resource allocation and market impacts (e.g. total supply and hired labour use) of restrictions on GHG emissions. A constrained optimisation analytical approach allows the assessment of counterfactual outcomes based on additional constraints – allowed amounts of GHG emissions – that are difficult to assess with other approaches and the currently available data. The linear optimisation approach is employed in this case due to data limitations, although linear (or linearised) models have been applied commonly in many similar types of analyses (Van Wijk *et al*. 2014; Sempore *et al*. 2015).

2.1 Geographic setting and site selection

The study sites were located in Kano and Jigawa States in Nigeria (Figure 1). Kano State belongs to the Sudan ecological zone and is the most extensively irrigated state in the country (NAERLS & PRSD 2012). The homogeneity of the tree, crop and livestock production systems was responsible for the random selection of Bunkure local government area (LGAs) from 44 LGAs in Kano using the card method developed by the Food and Agriculture Organization of the United Nations and the CGIAR Research Program on Climate Change, Agriculture and Food Security ([FAO & CCAFS] 2012). Maigateri LGA in Jigawa State was purposively selected as an area with representative current tree, crop and livestock production practices due to the large number of livestock and its proximity to Zinder region in the Republic of Niger, where successful climate-smart technologies are already established (Reij & Smaling 2008). Both LGAs are characterised by numerous smallholder farms integrating grain (sorghum) and legume crops (soybean and groundnut), trees (locust bean [*Parkia biglobosa*] and camel's foot [*Piliostigma reticulatum*]), and livestock (cattle, goats and sheep). Sorghum grain and legume seeds are consumed by humans and the residues (fodder and bran) are fed to animals or sold. Leaves and seed pods from tree pods are used as animal feed, and branches and trunks are used for fuel.

2.2 Specification of farm-level optimisation model

The optimisation model maximises the value of household agricultural production during a single year (with monthly periods for labour) subject to resource constraints (regarding land and labour), purchased input requirements, selected biophysical interactions among components of the crop–tree–livestock production system (such as the use of residues for animal feed), livestock nutrient requirements and restrictions on GHG emissions. The model assumes fixed quantities to describe the input requirements for each of the components.

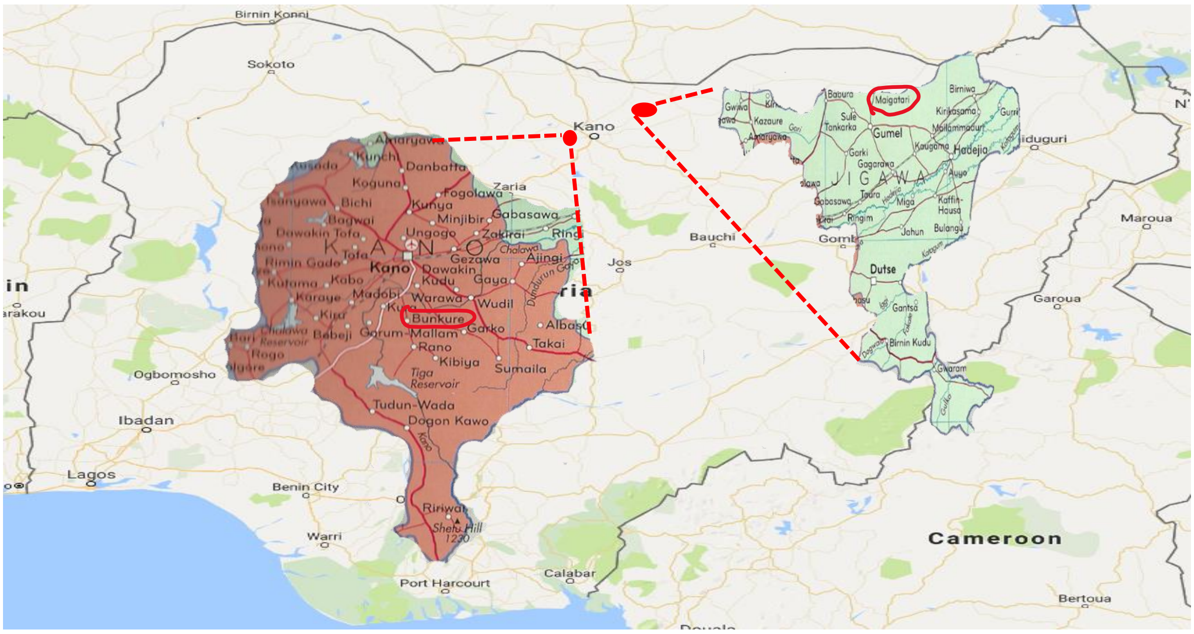

Figure 1: Locations of the study sites – Maigateri in Jigawa State and Bunkure in Kano State

2.2.1 Objective function

The objective function to be maximised is:

$$Z = \sum_{j=1}^{3}\sum_{p=1}^{8} \mathrm{CROPPROD_{jp}} \cdot \mathrm{CROPPRICE_{jp}}$$
$$+ \sum_{a=1}^{3}\sum_{q=1}^{3} \mathrm{ANPROD_{aq}} \cdot \mathrm{ANPRICE_{aq}}$$
$$- \sum_{a=1}^{3}\sum_{i=1}^{4} \mathrm{INPUTUSE_{i}} \cdot \mathrm{INPRICE_{i}}$$

$$- \textstyle\sum_{m=1}^{12} \mathrm{WAGE} \cdot \mathrm{HIREDLAB_{m}},$$

where the subscripts are defined as follows:
j is crop activity (one tree species, two crops at each location)
p is crop product (grain, bran, hull, fodder, pod, pod valve, branch, trunk)
a is animal activity (three livestock species: cattle, sheep, goats)
q is animal product (milk, meat, manure)
i is input (N fertiliser, urea, seed, other agricultural chemicals) and
m is month of the year;

and the variables are defined as:
Z = annual value of all farm production less cash costs
$CROPPROD_{jp}$ = annual production of product P from tree or crop activity J
$CROPPRICE_{jp}$ = sales price per unit of product P from tree or crop activity J
$ANPROD_{aq}$ = annual production of product Q from animal species A

$ANPRICE_{aq}$ = sales price per unit of product Q from animal species A
$INPUTUSE_i$ = annual use of purchased input I
$INPRICE_i$ = purchase price per unit of input I
$WAGE$ = hourly wage paid to hired labour (same in all months)
$HIREDLAB_m$ = hours of hired labour in month M

This objective function maximises the total value of products derived from farm production activities,[1] less the costs of hired labour and the value of purchased inputs. The activities that generate revenue for the farm household include trees,[2] sorghum, legumes,[3] cows, goats and sheep, each of which has sub-products used as inputs on the farm or sold (see the table in Appendix 1). A total of 20 (*j, p*) combinations of activities and sub-products are represented. Purchased inputs include fertiliser (NPK mix and urea), an aggregation of agricultural chemicals, and seed for grains and legumes.

2.2.2 Tree, crop and animal production

The quantities of tree and crop products generated by the farm household are a function of land allocated to each of the three tree and crop activities and associated product yields:

$$\mathrm{LAND_j} \cdot \mathrm{YIELD_{jp}^{CROP}} = \mathrm{CROPPROD_{jp}},$$

where
$YIELD^{CROP}_{jp}$ = annual yield per hectare of product P from tree or crop activity J;
$CROPPROD_{jp}$ = annual production of product P from tree or crop activity J.

This equation indicates that the physical quantity of production of product P from tree or crop activity J is equal to the product yield per hectare times the amount of land allocated to the activity.

The quantities of animal products generated by the farm household are a function of the number of animals kept and the yield of products per animal species per year:

$$\mathrm{ANIMALS_a} \cdot \mathrm{YIELD_{aq}^{ANIMAL}} = \mathrm{ANPROD_{aq}},$$

where
$YIELD^{ANIMAL}_{aq}$ = annual yield per animal of product Q from animal species A;
$ANPROD_{aq}$ = annual production of animal product Q from animal species A.

This equation indicates that the physical quantity of produced of product Q from livestock species A is equal to the product yield per animal times the number of animals.

2.2.3 Land and labour constraints

Land and labour are basic farm household resource constraints. Land in the study area is often classified into upland and lowland. The upland was modelled because it is the predominant land type used for rainfed production. The land constraint equation for the farm household was:

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[1] This is a "full income" specification that includes the total value of production, i.e. the sum of product sold by the household plus the value (at market prices) of product consumed by the household, which is a better representation of welfare based on income than the value of product sold.
[2] Tree species are locust bean (*Parkia biglobosa*) in Bunkure and camel's foot (*Piliostigma reticulatum*) in Maigateri.
[3] Legume species are soybean in Bunkure and groundnut in Maigateri.

$$\sum_{j=1}^{3} \mathrm{LAND_j} \leq \mathrm{HHLAND},$$

where
$LAND_j$ = hectares of land allocated to production of tree or crop J, and
$HHLAND$ = total cultivatable land available to the household.

This inequality ensures that the land used for crop or tree production is less than or equal to the total available for use by the household. The labour constraint is given by:

$$\sum_{j=1}^{3} \mathrm{CROPLAB_{jm}} \cdot \mathrm{LAND_j} + \sum_{a=1}^{3} \mathrm{ANLAB_{am}} \cdot \mathrm{ANIMALS_a} \leq \mathrm{HHLAB_m} + \mathrm{HIREDLAB_m},$$

where
$CROPLAB_{jm}$ = hours of labour required in month M for tree or crop activity J,
$ANLAB_{am}$ = hours of labour required in month M for animal species A, and
$HHLAB_m$ = hours of labour available from the farm household in month M.

The monthly hours of labour required equal the labour requirements per unit of land allocated to J, times the hectares of land use for J and per animal of species A, times the number of animals of species A, and this must be less than the sum of available household labour and hired labour.

2.2.4 Quantities of input used

The quantities of purchased inputs used for production are calculated based on land area and inputs required per hectare:

$$\sum_{j=1}^{3} \mathrm{LAND_j} \cdot \mathrm{INPUTREQ_{ij}} = \mathrm{INPUTUSE_i},$$

where
$INPUTREQ_{ij}$ = is the requirement of purchased input I per hectare of land used for tree or crop activity J, and
$INPUTUSE_i$ = total annual use of input I.

This equation indicates that the physical annual quantity of purchased input I used is equal to the amount of input I required per hectare times the amount of land allocated to the activity.

2.2.5 Animal nutrient requirements

Animal species represented in the model are assumed to require energy and protein for production, which must be consistent with both the minimum and maximum allowable quantities of dry matter (DM). The energy and protein constraints are specified as:

$$\mathrm{NUTREQ_{an}} \cdot \mathrm{ANIMALS_a} \leq \sum_{j=1}^{3} \sum_{p=1}^{8} \mathrm{FEED_{jpa}} \cdot \mathrm{NUTCONTENT_{jpn}},$$

where
$NUTREQ_{an}$ = the annual requirement of nutrient N (metabolisable energy, ME; crude protein, CP) per animal of type A,
$FEED_{jpa}$ = annual amount of product P from crop or tree J allocated to animal type A, and
$NUTCONTENT_{jpn}$ = content of nutrient N per product P from crop or tree type J.

The amount of two nutrients in the feed provided to animals of species A (amount fed times nutrient content) must be greater than the total requirements of those animals.

For the consumption of dry matter (DM) by animals, two equations are specified:

$$\mathrm{DMLOW_a} \cdot \mathrm{ANIMALS_a} \leq \sum_{j=1}^{3} \sum_{p=1}^{8} \mathrm{FEED_{jpa}} \cdot \mathrm{DMCONTENT_{jp}}$$
$$\sum_{j=1}^{3} \sum_{p=1}^{8} \mathrm{FEED_{jpa}} \cdot \mathrm{DMCONTENT_{jp}} \leq \mathrm{DMHIGH_a} \cdot \mathrm{ANIMALS_a},$$

where
$DMLOW_a$ is the minimum required annual DM intake for animal type A,
$DMCONTENT_{jp}$ is the DM content of the product P from crop or tree J, and
$DMHIGH_a$ is the maximum allowed annual DM intake for animal type A.

These two constraints imply that the annual DM in feed must be larger than a minimum required annual amount of DM intake by animal species A, but less than a maximum possible annual amount of DM (which is due to rumen fill constraints).

2.2.6 Balancing of tree, crop and animal products

The model also needs to ensure that the sources and uses of products in the model are consistent with a physical mass balance. This balance constraint for tree and crop activities is specified as:

$$\mathrm{HHREQCROP_{jp}} + \mathrm{CROPSALES_{jp}} + \sum_{a=1}^{3} \mathrm{FEED_{jpa}} + \mathrm{INTINPUT_{jp}} \leq \mathrm{CROPPROD_{jp}},$$

where
$HHREQCROP_{jp}$ = exogenous minimum annual allowable household use requirement of product P from tree or crop J, which includes uses as food, gifts, construction and fuel,
$CROPSALESj_p$ = annual amount sold of tree or crop product P from crop or tree type J, and
$INTINPUT_{jp}$ = amount of crop product P from crop or tree type J used as an intermediate input in other crops.

This constraint implies that the uses of tree and crop products are less than or equal to the amount available based on production. For animal products, an equation with a similar purpose is:

$$\mathrm{HHREQAN_{aq}} + \mathrm{ANSALES_{aq}} + \mathrm{MILKCALF_{aq}} \leq \mathrm{ANPROD_{aq}},$$

where
$HHREQAN_{aq}$ = exogenous minimum annual allowable household use requirement of product Q from animal type A,
$ANSALES_{aq}$ = annual amount sold of animal product Q from animal type A, and
$MILKCALF_{aq}$ = annual amount of milk needed to feed calves (cattle only).

This constraint implies that the uses of animal products are less than or equal to the amount available based on production. The requirements of households for tree, crop and livestock products ($HHREQCROP_{jp}$ and $HHREQAN_{aq}$) are assumed to be exogenous. This implies that satisfying the balance constraint will require the household to produce quantities sufficient to meet these requirements. This constraint is a key determinant of the "maximum allowable" GHG reductions, that is, the "maximum allowable reductions" must be consistent with meeting the assumed household requirements for tree, crop and animal products.

2.2.7 Manure balance

The model must also ensure that the use of manure required for crop production is consistent with the amount of manure produced by the animals:

$$\sum_{j=1}^{3} \mathrm{LAND_j} \cdot \mathrm{MANREQ_j} \leq \sum_{a=1}^{3} \mathrm{ANIMALS}_a \cdot \mathrm{MANURE_a},$$

where
$MANREQ_j$ = the annual amount of manure (from any animal species) required per hectare of land allocated to crop or tree J, and
$MANURE_a$ = the annual amount of manure produced per animal type A.

This constraint implies that the uses of manure in crop production are less than or equal to the total amount of manure (aggregated across all animal species) available based on animal production.

2.2.8 GHG emissions and restrictions

A key addition to this analysis compared to others using a farm-level optimisation model is the calculation of GHG emissions from farm activities, given as:

$$\sum_{j=1}^{3} \mathrm{LAND_j} \cdot \mathrm{GHGCROP_j} + \sum_{a=1}^{3} \mathrm{ANIMALS}_a \cdot \mathrm{GHGANIMAL_a} = \mathrm{TOTGHG},$$

where
$GHGCROP_j$ = the annual GHG emissions in CO_2 equivalents per hectare of land in activity J (for simplicity, this value does not include the effects of emissions from the application of lime, pre-farm operations during storage and transportation, as well as all mechanised farm operations, as these are minimal in this farming system),
$GHGANIMAL_a$ = the annual GHG emissions in CO_2 equivalents per animal of type A, and
TOTGHG = the total annual GHG emissions of the farm in CO_2 equivalents.

This equality calculates the total GHG emissions from farm tree, crop and livestock production. To assess the impacts of GHG reductions on farm activities and income, we specify an additional equation that limits GHG emissions:

$$\mathrm{TOTGHG} \leq \mathrm{GHGLIMIT},$$

where
GHGLIMIT = total annual GHG emissions allowed from the farm in CO_2 equivalents.

GHGLIMIT is the parameter modified in our scenarios to assess the effect on the objective function.

3. Data

The data to specify the parameters required for the optimisation model were derived from both primary and secondary sources. Primary data were obtained from a purposive sample using participatory rural appraisal (PRA) in the form of focus group discussions (FGD) and key-informant interviews. A total of 45 and 33 farmers participated in the FGD in Maigateri and Bunkure LGA respectively. A subsequent small-scale survey building on the FGD was administered to a random sample of 50 farm households in Maigateri and 55 farm households in Bunkure during the 2016/2017 production season. The FGD and survey (cited collectively as "field survey data" below) provide basic information about the characteristics of households and their farming systems. The size of the random sample was limited due to resource constraints, but the consonance between the FGD and the survey findings suggests that assumptions about household characteristics and farming systems are reasonably representative of some farm types at the two study sites. Secondary information to develop the empirical model included previous literature, publicly available market data and analyses conducted on a one-hectare field of sorghum-soybean under the canopy of eight locust bean trees in

Bunkure and sorghum/groundnut cultivation beneath six camel's foot trees in Maigateri LGA. The secondary data provided input requirements, product outputs and GHG emissions.

3.1 Tree data

The analysis includes two tree species that are commonly used by households in the two study sites: locust bean (*Parkia biglobosa*) in Bunkure LGA and camel's foot (*Piliostigma reticulatum*) in Maigateri LGA. For each tree species, the model includes the production of fodder, seed pods (pods, pod valves and fibrous material or "bran") and wood from the branches and the main trunk. Fodder is a key resource of tree production and is used as mulch and organic matter for grain production and as feed for livestock. The data required include the annual yields of the tree products, prices of outputs, inputs used in tree production and input prices. Yields were estimated based on secondary sources (see the table in Appendix 2). The productivity of trees in the Sudano–Sahelian savannahs was estimated to be between 2.5 m^3/ha/year and 3 m^3/ha/year, with per capita fuel wood consumption of between 0.75 m^3/day and 1.0 m^3/day (Agricultural Extension Research Liaison Services & Ahmadu Bello University [AERLS & ABU] 1988[4]). Fodder yields range from 10% to 12% of woodlot. Yield per ha of locust bean pod is between 350 kg/ha and 500 kg/ha, and daily/capita consumption of locust bean pod is between 1 g and 17 g (National Research Council [NRC] 2006). Values were converted into kilogram, with the mass obtained using a conversion factor of 750 kg/m^3 (Centre Technique Forestier Tropical (CTFT) 1989, cited in Stéphenne & Lambin 2001). Less published information is available for camel's foot species, which are more common in Maigateri LGA. We assumed yields at 50% for locust bean, based on a comparison of information about the two species from the Pl@ntUse website (2016a, 2016b). Prices of inputs and outputs and input use were derived from the field survey activities (FGD, key informant interviews and household surveys).

3.2 Crop data

The analysis includes the production of sorghum grain at both sites (both are located in the Sudan Savanna zone, where precipitation is insufficient to support maize production), as well as common legumes, viz. soybean in Bunkure LGA and groundnut in Maigateri. Fodder, grain and hull ("bran") are important resources from these crops and are used by the household for food, construction materials and livestock feed. Similar to the case with the trees, the required information about crops includes product yields, input requirements, and the prices of inputs and outputs (see the tables in Appendix 3 and Appendix 4). Yield data derived from the field surveys were complemented by published literature related to the use of crop by-products in livestock production. For example, by-products from sorghum and soybean/groundnut production were derived using the formula for harvest index in Powell *et al*. (1995) and Bayala *et al*. (2014). Input requirements were also derived from the field survey data, complemented with published sources (e.g. Powell *et al*. 2005; National Agricultural Extension and Research Liaison Services & Federal Department of Agricultural Extension [NAERLS & FDAE] 2014). Most input and output prices were developed based on field survey data, complemented for nitrogen fertiliser by valuation relationships from previous literature (NAERLS & FDAE 2014).

3.3 Livestock data

Three livestock species are commonly owned on farms at the two sites: cattle, goats and sheep. Cattle provide milk, whereas all species provide for the production of some meat and manure, the latter of which is used in the production of non-legume crops. The data included productivity per animal

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[4] Although this reference is dated, it is more complete than more recent citations, which nonetheless report values comparable to those assumed for our study.

species, including milk from cattle and average meat offtake and manure for all species (see Appendix 5). The animal-specific data required for modelling included the weight, average dry matter (DM) intake, yields of products and output prices (see Appendix 6). This information was derived from the field survey data, complemented by the relevant literature (Powell *et al*. 1995; Dupriez & De Leener 1998; Food and Agriculture Organization of the United Nations [FAO] 1998; Ayantunde *et al*. 2000, 2011). Manure is a key output, in addition to milk (from cattle) and meat, but its production is difficult to measure. Manure production per animal was estimated based on Powell *et al*. (1995) and Ayantunde *et al*. (2000).

In addition to the information on the animals, data were required on the nutritional value of the plant products used to feed livestock. These data comprise the DM, energy and protein content of fodder and the by-products of trees, sorghum and the two legume crops (Appendix 6). Data on dry matter (DM), metabolisable energy (ME) and crude protein (CP) were obtained from feed composition tables in Feedipedia (2017a, 2017b) and Dupriez and De Leener (1998). The recommended daily CP and DM requirement is 3% animal body weight (BW), with minimum recommended daily values of 2.5% and maximum possible values of 4.0% for cattle and 5.0% for sheep and goats. Per-animal ME requirements were 46.5 Megacalorie/day (Mcal/day) for cattle and 5.1 Mcal/day for sheep and goats. Values of ME for the maintenance of sheep, goats and cows producing less than five litres/day, derived by the FAO (1998), were adapted for the study area based on reported animal characteristics. Crude protein requirements for cattle were calculated as 0.4 kg/animal/day (for maintenance, growth and milk production), and 0.03 kg/animal/day for sheep and goats, based on animal characteristics from the field survey and FAO (1998) data on the animals' requirements.

3.4 GHG emissions data

Calculating the amount of GHG emissions from farm production was the main component of our analysis, but site-specific empirical measurements were not available – similar to the case in relation to many other sites (Ortiz-Gonzalo *et al*. 2017). As a result, we used the guidance provided by the Intergovernmental Panel on Climate Change (IPCC) to estimate GHG emissions for the farm-production activities at the two sites. (We did not include estimates of emissions related to household consumption or the marketing of products.) The IPCC (2006) defines three hierarchical tiers of methods used in the measurement of GHG emissions. These methods range from default emission factors and equations to the use of country-specific data and models to accommodate national circumstances. Generally, moving from tiers 1 to 3 improves the accuracy of estimation. However, it also increases the data needed for country-specific emission factors, as well as for land-use and management practices (i.e. activity data). In this study, the emission factors (EF) used to estimate GHG emissions were from the IPCC (2006) Tier 1 default equations based on data describing current farming systems in the region. A more detailed description of the methods used is provided in Appendix 7.

We used Tier 1 default methods and emission factors (EFs) from the 2006 version of the guidelines of the IPCC (2007) that considered management practices on soils managed with applied nitrogen fertiliser inputs. Because the estimated carbon (C) sequestered in soil organic matter is greater than the C produced by soils, net emissions from soil organic matter (biomass) are assumed to be zero. Another source of GHG emissions is from burning biomass (such as crop residues). Values of CO_2, nitrous oxide (N_2O), methane (CH_4), nitrogen oxides (NO_x) and carbon monoxide (CO) were calculated using biomass burned (0.01 tonnes DM/ha) multiplied by the applicable EF. Nitrous oxide (N_2O) emissions from soils comprise both direct and indirect components of a manure management system (MMS) and managed soil (MS). Other N_2O emissions are direct N emissions from nitrite (NO_3), ammonia (NH_3), and nitrous oxide (N_2O) from manure, tree and crop residues and fertiliser. All nitrous oxide emissions were converted to CO_2 equivalents (100-year global warming potential) using a multiplier of 310 from the IPCC (2007). The Tier 1 default EF of 0.20, which corresponds to

20% for $CO(NH_2)_2$, was used for calculating CO_2 emissions from urea fertilisation. IPCC (2006) indicates that CO and NO_x have limited direct global warming potential, so their effects are assumed to be zero. Production of sheep, goats and cows used for milk, meat, manure and draft results in CH_4 emissions from enteric fermentation and the MMS. The EFs for developing countries for sheep, goat and mature cows grazing on large areas were used to compute livestock-related methane emissions, which were then converted to CO_2 equivalents. In accordance with the IPCC (2007), a unit of CH_4 represents 21 units of CO_2eq.

Table 1: Household resources and requirements assumed for the optimisation model analysis

Characteristic	**Unit**	**Bunkure LGA**	**Maigateri LGA**	**Source information**
Household size	Person	5.0	5.0	Field survey data
Household labour	Person	3.0	3.0	Field survey data
Land area	ha	3.0	5.0	Field survey data; NAERLS & PRSD, 2012
Labour available	Person-days/year	480.0	480.0	Field survey data; AERLS & ABU 1988
Firewood requirement	kg/year	2 190.0	1 825.0	Field survey data; Stéphenne & Lambin 2001; AERLS & ABU 1988
Sorghum grain consumption	kg/person/year	1 790.0	924.0	Field survey data
Sorghum grain for gifts	kg/year	58.3	84.0	Field survey data
Sorghum fodder for construction	kg/year	76.3	378.0	Field survey data
Sorghum fodder for fuel	kg/year	645.9	302.4	Field survey data
Tree pod requirement	kg/year	19.7	6.8	NRC 2006
Milk consumption	l/year	136.9	136.9	Field survey data; Ayantunde *et al.* 2011
Legume grain consumption	kg/year	75.0	45.0	Field survey data
Cows owned	animal	1.0	2.0	Field survey data; Adegoke & Ayantunde 2014
Sheep owned	animal	5.0	12.0	Field survey data; Adegoke & Ayantunde 2014
Goats owned	animal	6.0	14.0	Field survey data; Adegoke & Ayantunde 2014

Table 2: Estimated greenhouse gas (GHG) emissions per unit of activities in the LP model

Source of emissions	**Units**	**Bunkure LGA**	**Maigateri LGA**
Locust bean/Camel's foot	kg CO_2eq/ha/year	176.5	153.5
Sorghum	kg CO_2eq/ha/year	364.6	331.6
Soybean/Groundnut	kg CO_2eq/ha/year	139.8	157.2
Cow	kg CO_2eq/animal/year	1 173.7	1 173.7
Sheep	kg CO_2eq/animal/year	193.0	193.0
Goat	kg CO_2eq/animal/year	134.0	134.0

Note: All values were calculated using methods described by the IPCC (2006) document based on input for practices and yields from field survey data and other secondary sources. The text provides additional descriptions of the specific calculations. Appendix 7 provides additional information and references.

3.5 Scenarios analysed

We determined a baseline scenario representing current production patterns and examined how production activities and household income would change subject to reductions in GHG emissions. Three scenarios were developed in addition to the baseline for each location:

- 10% reduction in GHG emissions compared to the baseline;
- 25% reduction in GHG emissions compared to the baseline;

- Maximum GHG emissions reduction for the Bunkure and Maigateri LGAs consistent with maintaining minimum household consumption requirements for tree, crop and animal products.

These scenarios allow an assessment of the magnitude of income-emissions trade-offs for different assumed reductions, motivated by the expectation that higher required reductions will imply larger household income reductions.

4. Results and discussion

Although many outputs could be reported from the optimisation analyses, we focused on the changes in full income, GHG emissions per farm per year and production patterns (Table 3). For each of the two LGAs, there exists a substantive trade-off between household income and reduction in GHG emissions, but the changes in production patterns and values of the trade-offs differ in the two areas, given their base production patterns and input usage. In both LGAs, the amount of foregone income to achieve a 10% reduction in GHG emissions is relatively small, at 1% and 3% in Bunkure and Maigateri respectively. The GHG emissions reduction was achieved by reducing livestock numbers by five sheep in Bunkure (half of the sheep numbers in the baseline) and by one cow and one sheep in Maigateri. This is consistent with the generally higher GHG emissions per unit of product from livestock, as discussed in previous work (e.g. International Livestock Research Institute [ILRI] 2006; Havlík *et al*. 2014; Herrero *et al*. 2014; De Pinto *et al*. 2016).

The achievement of greater reductions in GHG emissions, of 25%, requires more adjustments to the production pattern of the farm, which now include changes in cropping pattern in addition to livestock reductions. In Bunkure, the reduction is achieved by lower production of tree and soybean outputs, which is accompanied by a reduction in the use of urea as a fertiliser. In contrast, for Maigateri, the 25% reduction is accomplished through decreased planting of groundnut in addition to reductions in livestock. However, another relevant effect is that the Maigateri household now has less need of hired labour, which is decreased by more than one-third as a result of the reductions in groundnut production. This analysis indicates that, although the net proportional influence on optimal farm income is similar in the two LGAs (17% and 18% respectively), the changes required to achieve these (optimal) reductions differ based on the production system – which suggests that farming-systems specificity matters for the assessment of strategies to reduce GHG emissions.

The maximum allowable GHG reduction while maintaining recommended household consumption levels is 26% in Bunkure. This reduction is accomplished through an additional reduction in tree and soybean outputs and the associated use of urea, so the pattern and effect on income are relatively similar to the scenario requiring a 25% reduction. In Maigateri, the maximum reduction in GHG emissions while maintaining household tree, crop and animal product availability is 30%, and this is accomplished through the additional reduction of groundnut cultivation, so again the adaptation of the production pattern is similar to that for the 25% reduction scenario. Importantly, nearly all labour hired in the baseline scenario is no longer necessary to achieve the maximum possible reduction.

Requiring the reduction of GHG emissions on smallholder farms also affects the resource values (the marginal values of selected constraints, values not shown). In particular, the value of a marginal unit of land is reduced to zero if required reductions are 25%, which implies that the household would now not use all of its land (and by the assumptions of the model, would not rent it to other households, although this may be a possibility – but not one that would be likely to achieve the desired reduction in GHG emissions). The marginal value of internally generated inputs, like fodder and manure, is also lowered by the restrictions, given that there is less need for their use. Finally, the marginal value of livestock products increased due to the scarcity of the products and because household production is now constrained to the amount required for household consumption, which means that there are no longer revenues generated from livestock product sales.

It is useful to summarise the foregoing interactions between farm household welfare measured by full income and reductions in GHG emissions using two types of trade-off curves. An X-Y plot of GHG emissions and full income for the two LGAs (Figure 2) indicates the trade-offs between these outcomes, showing that initial reductions in GHG emissions require relatively limited foregone income, whereas the largest possible reductions in GHG emissions result in large income reductions. An alternative approach is to plot the costs of income foregone versus the achieved reductions in GHG emissions (Figure 3), which is conceptually similar to a marginal cost curve (in terms of income foregone) for reductions in GHG emissions. The marginal costs increase more rapidly for reductions in Bunkure than they do in Maigateri (although the starting income is also lower in Bunkure LGA). This implies that the costs of reductions in GHG emissions are likely to differ across production systems, which would suggest the need for additional site-specific analysis to inform decisions about least-cost GHG emissions strategies for smallholder agriculture in the region.

Table 3: Optimal farm-level tree-crop-livestock production decisions for the three GHG emissions scenarios in the Bunkure and Maigateri LGAs

Outcome or activity	**Units**	**Bunkure**				**Maigateri**			
		Baseline	**Difference with 10% GHG reduction**	**Difference with 25% GHG reduction**	**Difference with maximum GHG reduction**	**Baseline**	**Difference with 10% GHG reduction**	**Difference with 25% GHG reduction**	**Difference with maximum GHG reduction**
Full farm income	000 ₦/y	**3 541**	-30	-587	-787	**1 473**	-49	-267	-650
GHG emissions	kg CO_2eq/y	**2 943**	-294	-736	-768	**3 057**	-306	-764	-932
Tree									
Locust bean/Camel's foot	ha	**2.1**	0.0	-0.4	-0.6	**1.5**	0.0	0.0	0.0
Crop									
Sorghum	ha	**0.8**	0.0	0.0	0.0	**0.9**	0.0	0.0	0.0
Soybean/Groundnut	ha	**0.1**	0.0	0.0	0.0	**2.7**	0.0	-0.4	-1.5
Animal									
Cow	head	**0**	0	0	0	**1**	-1	-1	-1
Sheep	head	**10**	-5	-5	-5	**5**	-1	-1	-1
Goat	head	**5**	0	0	0	**4**	0	0	0
Input use									
Nitrogen fertiliser	kg/year	**144**	0	0	0	**152**	0	0	0
Urea	kg/year	**188**	0	-22	-31	**141**	0	-10	-36
Seed	kg/year	**13**	0	0	0	**42**	0	-4	-16
Pesticide	kg/year	**1**	0	0	0	**4**	0	0	-2
Hired labour									
May	day/month	**0**	0	0	0	**68**	0	-39	-67
June	day/month	**0**	0	0	0	**387**	0	-103	-387
July	day/month	**0**	0	0	0	**302**	0	-103	-302

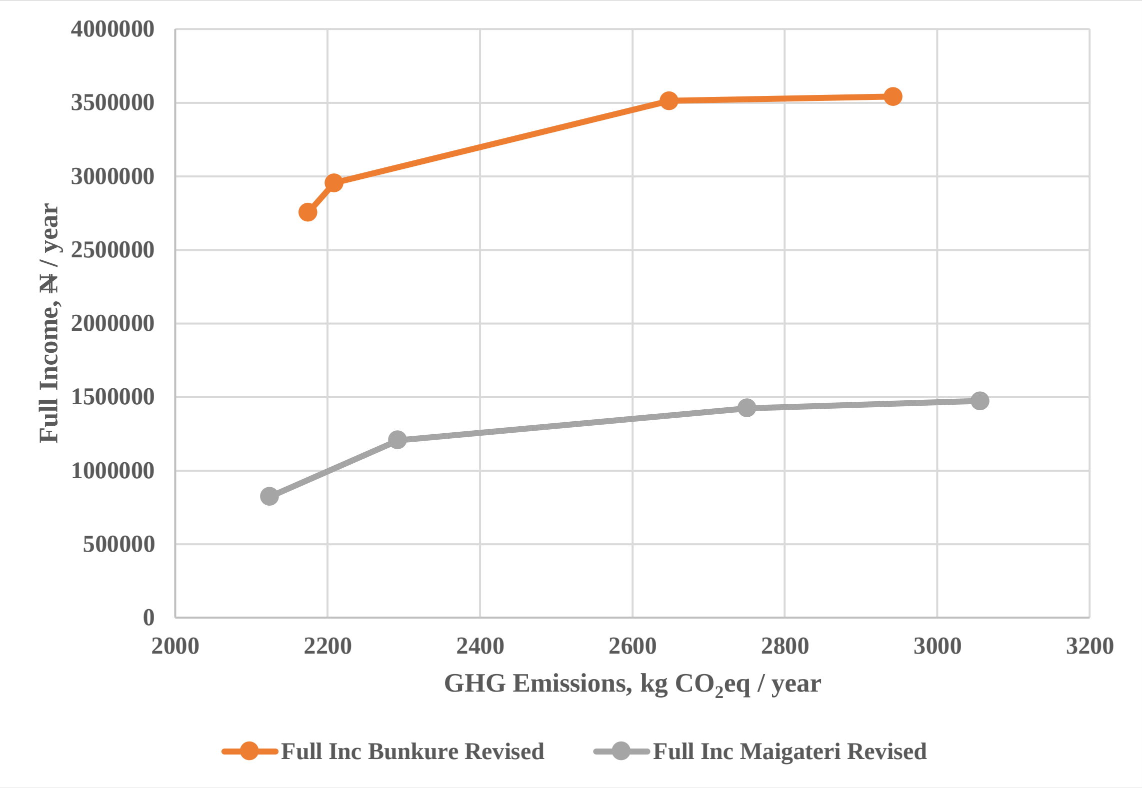

Figure 2: Farm-level GHG emissions and full farm-income values for baseline and three GHG reduction scenarios (10%, 25% and maximum possible consistent with household requirements (26.1% and 30.5% in Bunkure and Maigateri LGA respectively))

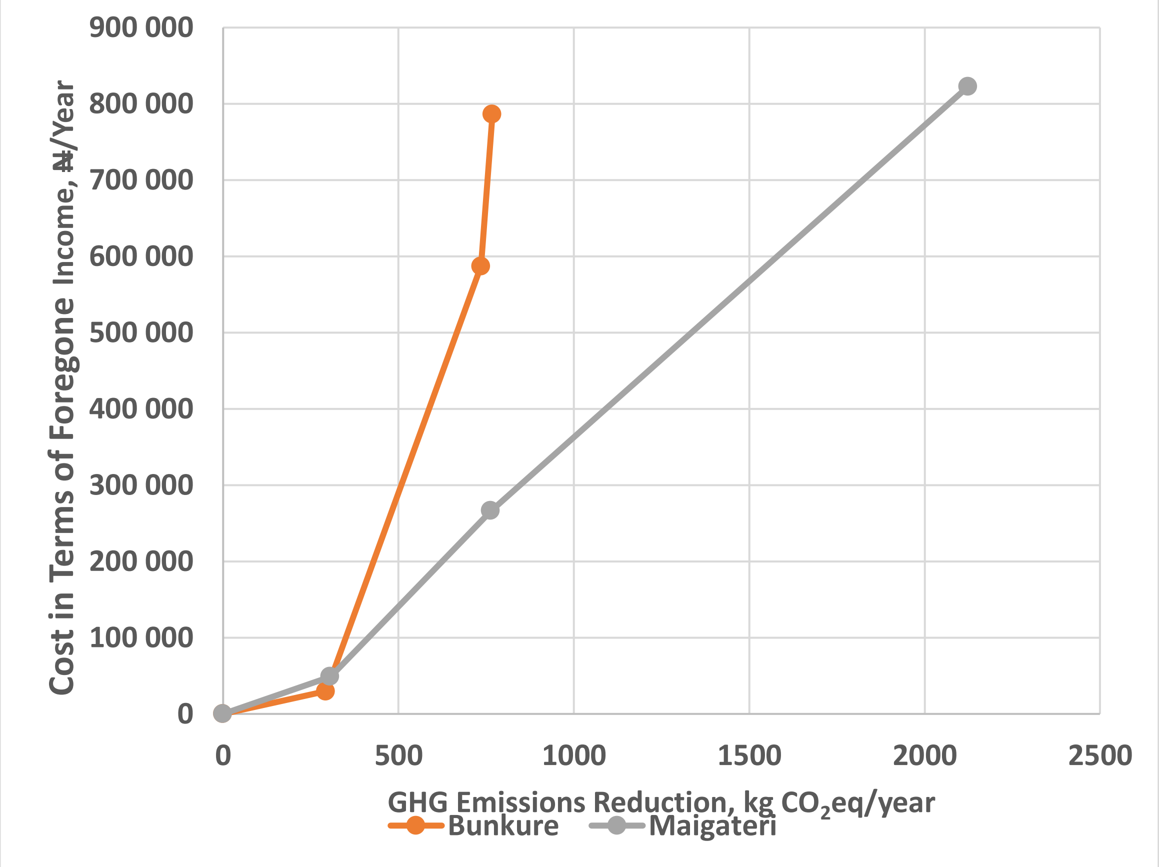

Figure 3: Marginal cost (foregone income) curves for GHG emission reductions for baseline and three GHG reduction scenarios (10%, 25% and maximum possible consistent with household requirements (26.1% and 30.5% in Bunkure and Maigateri LGA respectively))

5. Conclusions and implications

A key finding of our analysis is that reducing GHG from smallholder agricultural activities in this region using current production methods would require substantive changes from current agricultural production patterns and reductions in farm income. Reductions in income with increasingly restrictive constraints on farm-level GHG emissions are not surprising, because by its nature a more constrained optimisation problem cannot show an improvement in the value of the objective function. Thus, the contribution of this work is to highlight the empirical magnitude of the effect of restrictions on farm household incomes, production patterns, resource use and resource values. Our analysis also suggests that these influences could transcend those on the farms analysed through their effect on quantities of hired labour, and through market availability of products due to reductions in sales by farm households. Productivity-enhancing technologies may offer a means to enhance income and reduce GHG emissions, but require further research.

5.1 Limitations and extensions

Our analysis provides an initial conceptual and empirical framework for subsequent research, which would appear both useful and necessary given the diversity of responses observed for (only) the two different smallholder farm households we analysed. However, it is important to note a number of limitations in our analysis that might be addressed in future studies. First, the optimisation model developed for this study has a relatively simple structure due to limited data availability. Mean values are used to represent most parameters, and variation in costs, prices and production are not considered in the analysis, which omits the potential influences of cross-sectional and inter-annual variation that could be important to assess potential strategies to reduce GHG emissions and their trade-offs. Future work could usefully include the assessment of the influences of variation in these key assumptions. Additional data on farmer risk preferences or the use of a quadratic programming approach (Hazell & Norton 1986) would allow the mapping of a risk-efficient production frontier with and without restrictions on GHG emissions, which would complement and extend the findings of this study. However, this analysis would require data on a range of prices, yields and related emissions that would require substantive resources to obtain. Implicitly, this implies another potentially useful extension of our analysis to include the explicit representation of multiple years, which would also facilitate the representation of tree and livestock production that take place over longer time scales.

Second, the opportunities for a reduction in GHG emissions and the effects on income were conditioned on maintaining an assumed minimum recommended consumption of tree products, crops and livestock produced by the household. We assumed this to avoid potential negative (direct) nutritional effects on the household from required reductions in GHG emissions – although indirect nutrition, health and educational effects are also possible due to reduced incomes. More sophisticated representations of household demand, as in Bakker *et al*. (2018) and Wossen *et al*. (2018), and clearer demarcation of the effects on different dimensions of food security (availability, access and utilisation), as described in Nicholson *et al*. (2021), would highlight other potentially important trade-offs between food security and GHG emissions.

Importantly, our analysis assesses the effects of reductions based on the characteristics of current (average) production technologies. As noted above, constraining GHG emissions without modifications to system components will lead inevitably to reductions in household welfare as measured by full income. Thus, addition analyses of the feasibility and benefits of new technologies or practices that combine higher yields and lower per-unit GHG emissions would be a key extension of this study. Previous studies (e.g. Bellarby *et al*. 2014; York & Rymer 2017; Tariq *et al*. 2018) illustrate the types of methods required and information generated, but analyses are not yet available for the northern Nigerian context, nor do they integrate this knowledge into multiple-product farm optimisation models to assess their fit within specific farming systems. The optimisation model framework we have applied in this study could be extended to include these alternative production practices, allowing the identification of those that best mitigate income-GHG emissions trade-offs. Productivity increases for livestock may be particularly important, given the proportion of GHG emissions arising from enteric fermentation (Ortiz-Gonzalo *et al*. 2017) and the reductions in animal numbers indicated in our analyses. Alternative complementary technologies, such as biochar cookstoves (Sundberg *et al*. 2020), may also modify the resource requirements (e.g. for fuelwood) of households and allow reductions in emissions. However, even with the availability of improved technologies, it is possible that income-GHG emissions trade-offs will persist, depending on the emission reductions desired from smallholder farms.

Another limitation of our study is the relatively small sample of farms and the limited regional coverage of the empirical analyses. Although the farms analysed appear to be representative of common farm types in the northern Nigeria region based on previous literature (Ajiegbe *et al*. 2010; Berkhout *et al*. 2011; Usman & Nichol 2018; Yusuf *et al*. 2018; Ayinde 2019), diversity in the characteristics of farms within the region make it difficult to generalise our empirical findings about changes to income and production activities, other than the above-noted conclusion that restrictions on GHG emissions will have a negative effect on income. However, the use of representative farm types at the two sites and with different production characteristics provides some initial evidence that effects may be similar for other types of farms within the region studied. In addition to addressing the other limitations discussed above, additional site-specific data collection and analyses are needed to reach generalisable conclusions with regard to the influences of GHG restrictions on household welfare.

5.2 Implications for research, extension and policy

Above we have highlighted a number of implications for research, including the need for improved model representations, a broader scope of data collection and the further development and evaluation of productivity-enhancing technology with lower GHG emissions per unit of product. In addition, it is relevant to improve the knowledge base on the sources of GHG emissions in smallholder farming systems (as in Ortiz-Gonzalo *et al*. 2017). This will allow an improved and more site-specific empirical basis for the assessment and mitigation of emissions. Taken together, these knowledge gaps suggest the need for programmatic and policy actions related to the allocation of funds to agriculture research for development (A4RD), both by national systems and the CGIAR.

In addition to the implications for knowledge generation, our analysis suggests that reductions in GHG emissions in the absence of changes to production practices would require compensatory payments to smallholder farmers to avoid placing the burden of reducing GHG emissions on the region’s smallholder farmers. Although less common in lower-income country settings, payments of this nature mirror those made for environmental services in some higher-income country settings (Ezzine-de-Blas *et al*. 2016). In practice, such a payments programme would also require both funding support and administrative resources and capacity to be implemented effectively. This may imply that other strategies for national-level GHG reduction could be more cost-effective, even within the agriculture sector. There is likely to be an important role for the development and implementation of improved technologies that reduce total GHG emissions, not just per-unit emissions, given the future growth in production levels necessary to meet the needs of a growing population. If an emissions-reduction effort, a payments programme and/or the dissemination of improved technological options were implemented, this would also require enhanced training and resources for relevant extension personnel, e.g. to provide information on the best means of reducing emissions, receiving payments or integrating new practices into farming systems. For now, we are unaware of substantive policy proposals that would require GHG reductions by smallholders at the study sites, but as efforts to reduce GHG emissions accelerate, the information provided by this and similar studies may take on additional importance.

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Appendices

Appendix 1: Activity–product and input requirement combinations allowed in the farm models for the two sites

Location (LGA)	**Associated Products (p)**										
Model activity (j)	Fodder	Pod	Pod valve	Bran	Branch	Trunk	Grain	Hull	Milk	Meat	Manure
Bunkure LGA only											
Locust bean (tree)	X	X	X	X	X	X					
Soybean	X			X			X	X			
Maigateri LGA only											
Camel’s foot (tree)	X	X	X	X	X	X					
Groundnut	X			X			X				
Both LGA											
Sorghum	X			X			X				
Cattle									X	X	X
Goats										X	X
Sheep										X	X

Maigateri LGA

	Purchased inputs (i)				**Products from other model activities**							
Model activity (j)	N fertiliser	Urea	Seed	Ag chemical	Camel’s foot fodder	Camel’s foot pod valve	Camel’s foot bran	Sorghum fodder	Sorghum bran	Groundnut fodder	Groundnut bran	Manure
Maigateri LGA only												
Camel’s foot (tree)		X	X	X								X
Groundnut		X	X	X								
Sorghum	X	X	X	X	X							X
Livestock production					X	X	X	X	X	X	X	

Bunkure LGA

	Purchased inputs (i)				**Products from other model activities**							
Model activity (j)	N fertiliser	Urea	Seed	Ag chemical	Locust bean fodder	Locust bean pod valve	Locust bean bran	Sorghum fodder	Sorghum bran	Soybean fodder	Soybean bran	Manure
Bunkure LGA only												
Locust bean (tree)		X	X	X								X
Soybean		X	X	X								
Sorghum	X	X	X	X	X							X
Livestock production					X	X	X	X	X	X	X	

Note: The specification of activity, product and input combinations represented in the farm optimisation models were defined based on field survey data and secondary sources.

Appendix 2: Description of tree-production activities

Production-related characteristic	**Units**	**Bunkure LGA (Locust bean, *Parkia biglobosa*)**	**Maigateri LGA (Camel's Foot, *Piliostigma reticulatum*)**	**Source information**
Yields				
Fodder	kg/ha/y	618.9	309.4	AERLS and ABU 1988; Powell *et al.* 1995
Pods	kg/ha/y	1 608.8	804.4	AERLS and ABU 1988; NRC 2006
Pod valves	kg/ha/y	371.3	185.6	AERLS and ABU 1988
Bran	kg/ha/y	866.3	433.1	AERLS and ABU 1988; NRC 2006; Powell *et al.* 1995
Branch	kg/ha/y	2 475.0	1 237.5	AERLS and ABU 1988; Stéphenne and Lambin 2001; NRC 2006; Powell *et al.* 1995
Trunk	kg/ha/y	6 435.0	3 217.5	AERLS and ABU 1988; NRC 2006
Prices of Outputs				
Fodder	Naira/kg	5.82	1.62	Field survey data
Pods	Naira/kg	450.00	20.00	Field survey data
Pod valves	Naira/kg	1.24	1.14	Field survey data
Bran	Naira/kg	72.00	20.00	Field survey data
Branch	Naira/kg	38.17	15.27	Field survey data
Trunk	Naira/kg	32.63	4.35	Field survey data
Input Requirements				
Seeds	kg/ha/y	0.1	0.1	Field survey data
Urea	kg/ha/y	50.0	25.0	Field survey data
Agricultural chemicals	l/ha/y	0.2	0.1	Field survey data
Manure	kg/ha/y	166.7	83.3	Field survey data
Prices of Inputs				
Seeds	Naira/kg	200.00	95.00	Field survey data
Urea	Naira/kg	156.00	156.00	Field survey data; Powell *et al.* 1995
Agricultural chemicals	Naira/l	1 600.00	1 600.00	Field survey data
Manure	Naira/kg	13.00	10.00	Field survey data

Appendix 3: Description of sorghum-production activities

Production-related characteristic	**Units**	**Bunkure LGA**	**Maigateri LGA**	**Source information**
Yields				
Grain	kg/ha/y	2 330.0	1 200.0	Field survey data
Fodder	kg/ha/y	2 935.8	1 512.0	Field survey data; Powell *et al.* 1995; Bayala *et al.* 2014
Bran	kg/ha/y	80.0	36.0	Field survey data
Prices of outputs				
Grain	Naira/kg	450.00	72.00	Field survey data
Fodder	Naira/kg	0.68	1.32	Field survey data
Bran	Naira/kg	0.00	0.00	Field survey data
Input requirements				
Seeds	kg/ha/y	14.0	14.0	Field survey data
Nitrogen fertiliser	kg/ha/y	175.0	175.0	Field survey data; NAERLS and FDAE 2014
Urea	kg/ha/y	100.0	43.8	Field survey data
Agricultural chemicals	l/ha/y	1.0	1.0	Field survey data
Manure	kg/ha/y	330.0	630.0	Field survey data
Tree fodder	kg/ha/y	232.1	126.8	AERLS and ABU 1988; Powell *et al.* 1995
Legume fodder	kg/ha/y	30.2	75.6	Field survey data
Prices of inputs				
Seeds	Naira/kg	180.00	400.00	Field survey data
Nitrogen fertiliser	Naira/kg	130.00	50.00	Field survey data; Powell *et al.* 1995; NAERLS and FDAE 2014
Urea	Naira/kg	156.00	156.00	Field survey data
Agricultural chemicals	Naira/l	1 600.00	16 00.00	Field survey data
Manure	Naira/kg	13.00	10.00	Field survey data

Appendix 4: Description of legume crop-production activities

Production-related characteristic	**Units**	**Bunkure LGA (soybean)**	**Maigateri LGA (groundnut)**	**Source information**
Yields				
Grain	kg/ha/y	1 200.0	1 000.0	Field survey data
Fodder	kg/ha/y	1 512.0	1 260.0	Field survey data; Powell *et al.* 1995; Bayala *et al.* 2014
Bran	kg/ha/y	40.0	5.0	Field survey data
Hull	kg/ha/y	15.0	0.00	Field survey data
Prices of outputs				
Grain	Naira/kg	400.00	417.00	Field survey data
Fodder	Naira/kg	0.40	0.48	Field survey data
Bran	Naira/kg	0.00	0.00	Field survey data
Hull	Naira/kg	0.00	0.00	Field survey data
Input requirements				
Seeds	kg/ha/y	12.0	11.0	Field survey data
Urea	kg/ha/y	0.0	25.0	Field survey data
Agricultural chemicals	l/ha/y	1.0	1.0	Field survey data
Prices of inputs				
Seeds	Naira/kg	150.00	350.00	Field survey data
Urea	Naira/kg	156.00	156.00	Field survey data
Agricultural chemicals	Naira/l	1 600.00	1 600.00	Field survey data

Appendix 5: Description of activities related to ruminant animals (cows, sheep and goats)

Production-related characteristic	**Units**	**Bunkure LGA**	**Maigateri LGA**	**Source information**
Species, breed				
Cow	–	Sokoto Gudali	Red Bororo	Field survey data
Sheep	–	Uda	Uda	Field survey data
Goat	–	Red Sokoto/Maradi	Red Sokoto/Maradi	Field survey data
Species, yields				
Cow				
Meat	kg/animal/y	173.0	203.0	Field survey data; Powell *et al*. 1995; Ayantunde *et al*. 2000; IPCC 2006
Milk	l/animal/y	684.4	684.4	Field survey data; Ayantunde *et al*. 2011
Manure	kg/animal/y	1027.4	1027.4	Field survey data; Powell *et al*. 1995; Ayantunde *et al*. 2000
Sheep				
Meat	kg/animal/y	28.0	28.0	Field survey data; IPCC 2006; Ayantunde *et al*. 2007
Milk	l/animal/y	0.0	0.0	Field survey data
Manure	kg/animal/y	102.7	102.7	Field survey data; Powell *et al*. 1995; Ayantunde *et al*. 2000
Goat				
Meat	kg/animal/y	30.0	30.0	Field survey data; Powell *et al*. 1995; Dupriez and De Leener 1998
Milk	l/animal/y	0.0	0.0	Field survey data
Manure	kg/animal/y	102.7	102.7	Field survey data; Powell *et al*. 1995; Ayantunde *et al*. 2000
Species, body weight				
Cow	kg/animal	350.0	350.0	FAO 1998
Sheep	kg/animal	20.0	20.0	FAO 1998
Goat	kg/animal	20.0	20.0	FAO 1998
Prices of outputs				
Cow				
Meat	Naira/kg	1000.0	850.0	Field survey data; NAERLS and FDAE 2014
Milk	Naira/l	150.0	100.0	Field survey data
Manure	Naira/kg	13.0	10.0	Field survey data
Sheep				
Meat	Naira/kg	770.0	502.0	Field survey data; NAERLS and FDAE 2014
Manure	Naira/kg	13.0	10.0	Field survey data
Goat				
Meat	Naira/kg	715.0	455.0	Field survey data; NAERLS and FDAE 2014
Manure	Naira/kg	13.0	10.0	Field survey data
DM intake, species				
Cow	kg DM/animal/y	4562.5	4562.5	Powell *et al*. 1995; Stéphenne and Lambin 2001
Sheep	kg DM/animal/y	456.3	456.3	Powell *et al*. 1995; Stéphenne and Lambin 2001
Goat	kg DM/animal/y	456.3	456.3	Powell *et al*. 1995; Stéphenne and Lambin 2001

Appendix 6: Nutrient values of animal feed

Nutrient, feed source	**Units**	**Bunkure LGA**	**Maigateri LGA**	**Source information**
Dry matter				
Tree				
Fodder	%DM	56.8	28.3	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017b
Pod valve	%DM	91.3	57.9	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017a
Bran	%DM	93.0	97.0	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017a
Sorghum				
Bran	%DM	89.8	89.8	Heuzé *et al*. 2015a
Fodder	%DM	28.1	28.1	Heuzé *et al*. 2015b
Legume				
Bran	%DM	89.1	95.5	Heuzé *et al*. 2017a, 2017b
Fodder	%DM	24.0	91.2	Heuzé *et al*. 2016, 2017c
Crude protein				
Tree				
Fodder	%CP	12.0	1.7	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017b
Pod valve	%CP	13.4	2.2	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017a;
Bran	%CP	4.7	1.2	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017a;
Sorghum				
Bran	%CP	13.2	11.7	Heuzé *et al*. 2015a
Fodder	%CP	3.5	3.5	Heuzé *et al*. 2015b
Legume				
Bran	%CP	13.1	46.0	Heuzé *et al*. 2017a, 2017b
Fodder	%CP	15.7	4.9	Heuzé *et al*. 2016, 2017c
Metabolisable energy				
Tree				
Fodder	MJ ME/kg DM	4.8	6.0	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017b
Pod valve	MJ ME/kg DM	10.7	8.4	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017a
Bran	MJ ME/kg DM	8.9	6.1	Annex 2 in Dupriez & De Leener 1998; Feedipedia 2017a
Sorghum				
Bran	MJ ME/kg DM	13.2	13.2	Heuzé *et al*. 2015a
Fodder	MJ ME/kg DM	3.5	3.5	Heuzé *et al*. 2015b
Legume				
Bran	MJ ME/kg DM	11.6	28.2	Heuzé *et al*. 2017a, 2017b
Fodder	MJ ME/kg DM	9.2	7.2	Heuzé *et al*. 2016, 2017c

Appendix 7: Details of calculations of greenhouse gas emissions (Adapted from Ayinde 2019)

The Intergovernmental Panel on Climate Change ([IPCC] 2006) defines three hierarchical tiers of methods used in the measurement of GHG emissions. These methods range from default emission factors and equations to the use of country-specific data and models to accommodate national circumstances. Generally, moving from tiers 1 to 3 improves the accuracy of estimation. However, it also increases the data needed for country-specific emission factors, as well as the data needed for land-use and management practices (i.e. activity data). In this study, the emission factors (EF) used to estimate GHG emissions were taken from the IPCC (2006) Tier 1 default equations based on data describing current farming systems in the region.

Tier 1 uses default assumptions and equations but lacks the data and resources required for calculating more accurate, country-specific emission factors, as well as land-use and management practices (Bryan *et al*. 2013; Dunkelberg *et al*. 2014). If necessary, a combination of tiers can be employed in which Tier 1 is partly or wholly immersed in national data as part of a Tier 2 estimation, as represented in the Cool Farm Tool version 1.0 (Hillier *et al*. 2011; Bellarby *et al*. 2014). It could also require the use of methods and data on Tier 1 inventories that are applicable to Tier 2 inventories (Eleto Torres *et al*. 2015; Goopy *et al*. 2015). Paul *et al*. (2017) used Tier 2 guidelines to estimate emissions from enteric fermentation (CH_4) for local and crossbred cattle breeds with gross energy requirements for an annual milk production of 340 l year^{-1} and 680 l year^{-1} respectively. This resulted in calculated emission factors of 20 kg CH_4 head^{-1} year^{-1} for local cattle and 26 kg CH_4 head^{-1} year^{-1} for crossbred cattle. Tier 1 default emission factors for other livestock led to 5 kg CH_4 head^{-1} year^{-1} for sheep and goats.

Tier 3 methods involve having a proper grasp of soil and agronomic practices to operate efficiently. They also involve using process-based modelling, such as DAYCENT (Del Grosso *et al*. 2001), InfoCROP (Aggarwal *et al*. 2004), WNMM (Li *et al*. 2005) and DeNitrification-DeComposition (DNDC) crop models (Li 2000). Li (2007) used DNDC to estimate spatially explicit profiles of GHG emissions from cropland with varying crop genetic productivity shifters, management systems and climate scenarios.

Tier 3 methods could even require more detailed measurements, such as TechnoGAS (Wassmann & Pathak, 2007), which entails combining with and reconciling other models. For instance, De Pinto *et al*. (2016) applied the DNDC model of Li (2007), along with two other models, to illustrate that policies that increase efficiency in livestock productivity and reduce land allocated to pasture are better than those that singly target deforestation or separately reduce emissions from crop production in Colombia. In general, these approaches require a great deal of data, as illustrated by De Oliveira Silva *et al*. (2015).

The activity-specific GHG emissions estimates used in this study (Table 1, after the references for Appendix 7) were obtained using IPCC (2006) Tier 1 equations and guidelines. GHG included the effects of biomass change, dead organic matter (OM), soil carbon, non-CO_2 from burning, livestock methane (CH_4) emissions from the manure management system (MMS) and enteric fermentation in kg CH_4/year, as well as CO_2 emissions from urea fertilisation. A Tier 1 default emission factor (EF) of 0.20, equivalent to the carbon (C) content of urea on an atomic weight basis (20% for $CO(NH_2)_{2,}$) was used. CO_2–C emissions were converted to CO_2 by multiplying the values obtained by 44/12.

Other estimations included indirect N_2O emissions from volatilisation and leaching from managed soils (MS) in kg N_2O/year, as well as direct N_2O emissions from manure management systems (MMS) in livestock and managed soils (MS) in kg N_2O-N/year. The IPCC Tier 1 methodologies do not consider different land cover, soil type, climatic conditions or management practices other than soils containing N inputs, which include NPK, urea, manure and leguminous crop residue biomass.

Further, they did not consider the time interval for direct emissions from crop residue N. Respondents in both LGAs utilised small quantities of agro-chemicals, fertiliser and concentrates; as a result, off-farm GHG emissions were excluded from the GHG inventory.

A sample calculation value of 0.5 tonnes/ha for agricultural residue biomass burned was used, but it might be zero. Values for mass burnt, which includes CO_2, N_2O, CH_4, NO_x and carbon monoxide (CO) was set at 0.01 tonnes DM/ha, with a value of 0.8 adopted as combustion factor (cf) for maize residues. Values for non-CO_2 emissions from mass burning and cf were multiplied with the emission factor for the burning of agriculture residues (G_{ef}, i.e. CO_2 (1 515), N_2O (0.07), CH_4 (2.7), NO_x (2.5) and CO (92)) to obtain estimates of non-CO_2 emissions from mass burning of locust bean, camel's foot, sorghum, groundnut and soybean residues for the study sites. The model assumes the conversion of carbon monoxide (CO), which has weak direct global warming potential, while NO_x may reduce warming, thus the CO_2eq factor was set at zero.

Given that the estimated C harvest is greater than the default C production for the tropical dry setting, the Tier 1 method assumes that carbon stock changes are zero and that dead wood and litter stocks present in cropland, agroforestry systems and orchards are at equilibrium. Subsequently, a conservative assumption of no net biomass accumulation for camel's foot and locust bean was adopted. According to Paul *et al*. (2017), changes in soil organic carbon (SOC) stocks are slow and difficult to estimate, corroborating the findings of Palm *et al*. (2010) and Powlson *et al*. (2016). Thus, there was no need to estimate the carbon stock changes and dead organic matter (OM) needs in this system. However, this is contrary to much of what seems to be the case regarding soil organic matter (SOM) content in African contexts (e.g. Tully *et al*. 2015), which suggests a downward trend. Thus, an assumption of no change in soil carbon is probably overly optimistic.

The primary focus of N_2O emissions in this study includes direct and indirect emissions from MMS and MS. The amount of manure per hectare used for estimation was obtained from the survey, and IPCC default nitrogen excretion rates were used to multiply with default EFs from the IPCC guidelines. Rates were presented in units of nitrogen excreted per 1 000 kg of animal per day and applied to cows, sheep and goats using a typical average animal mass (TAM). According to the FAO, TAM for developing countries is set at 350 kg for local cows and 20 kg for sheep and goats. It was assumed that over 90% of the manure produced per household was collected, and that all of it was applied to fields for fertilisation. All manure was also assumed to be managed in a solid storage system, but urine was ignored.

Other N_2O losses considered are direct emissions from NO_3, NH_3 and N_2 in nitrogen (N)-containing inputs such as manure, urine and dung, tree/crop residues and fertiliser in soils. Urine and dung inputs to freely grazed soils were also assumed to be small and thus were excluded from the model. The model assumes no harvest or return of below ground biomass, and only the application of fodder of soybean/locust bean and groundnut/camel's foot for sorghum production in Bunkure and Maigateri respectively. Nitrogen (N) content in a 50 kg bag of NPK fertiliser does not include urea and assumes a diammonium phosphate (DAP) composition for N fertiliser of 0.20 kg N. The study concluded the estimation of N_2O emissions using the atmospheric deposition of N volatilised from soils. All emissions were converted to N_2O by multiplying the values obtained by 44/28 (IPCC 2006).

Extensive production of ruminant livestock, which includes sheep, goats and particularly cows, is used for more than one production purpose – milk, meat and draft – and results in CH_4 emissions from enteric fermentation and MMS. The emission factors for developing countries that were used are 46 kg CH_4 $head^{-1}$ $year^{-1}$ for mature cows grazing on large areas, and 5 kg CH_4 $head^{-1}$ $year^{-1}$ for sheep and goats.

All results of the emission calculations were converted to carbon dioxide equivalents (CO_2e), considering the global warming power of each of the GHG based on their lifetime (years) and radioactive efficiency (W m^{-2} ppb^{-1}). In accordance with the IPCC (2007), a unit of CO_2, CH_4 and N_2O represents one, 21 and 310 units of CO_2e respectively.

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Table 1 (Appendix 7): GHG emissions from tree crop-livestock production activities

Location	**Bunkure**			**Maigateri**		
Crop component						
Emissions component	**Locust bean**	**Sorghum**	**Soybean**	**Camel's foot**	**Sorghum**	**Groundnut**
Unit	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**
Biomass	-	-	-	-	-	-
Dead organic matter	-	-	-	-	-	-
Soil carbon	-	-	-	-	-	-
Non-CO_2 from burning	127.5	127.5	127.5	127.5	127.5	127.5
Direct N_2O soils	10.1	142.3	12.3	6.6	146.4	11.4
Indirect N_2O soils	2.3	21.6	0.0	1.1	25.6	0.0
Urea	36.7	73.3	0.0	18.3	32.1	18.3
Total	*176.5*	*364.6*	*139.8*	*153.5*	*331.6*	*157.2*
Emissions component	**Cows**	**Sheep**	**Goats**	**Cows**	**Sheep**	**Goats**
Unit	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**	**(kg CO_2eq/ha/year)**
CH_4 emissions	987.0	172.2	109.6	987.0	172.2	109.6
N_2O emissions	186.7	20.8	24.4	186.7	20.8	24.4
Total	*1 173.7*	*193.0*	*134.0*	*1 173.7*	*193.0*	*134.0*