Multiple-year farm-level assessments of trade-offs between GHG emissions and income: case examples of two farming systems in Northern Nigeria

Taiwo Bintu Ayinde (taiyeayinde2006@yahoo.com)
Ahmadu Bello University, Division of Agricultural Colleges https://orcid.org/0000-0002-8250-8806
Charles F. Nicholson
Cornell University School of Integrative Plant Science
Benjamin Ahmed
Ahmadu Bello University Faculty of Agriculture

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Abstract

This study quantifies the trade-offs between welfare (measured by income) and greenhouse gas (GHG) emissions in two farming systems of northern Nigeria using data for five years from 2015 to 2019. The analyses employ a farm-level optimization model that maximizes value of production less purchased input costs for agricultural activities including production of trees (Locust Bean or Camel's Foot), sorghum, groundnut or soybeans and multiple livestock species. We compare income and GHG emissions without constraints to scenarios requiring reductions in emissions of either 10% or the maximum reduction feasible while maintaining minimum household consumption levels. For both locations and all years, we find that reductions in GHG emissions would lower household incomes and require substantive modifications to production patterns and input use. However, the extent to which reductions are possible and the patterns of income-GHG trade-offs vary, indicating that such effects are site-specific and time-variable. The variable nature of these trade-offs suggests challenges for the design of any program that would that seek to compensate farmers for reductions in their GHG emissions.

1 Introduction

Much of the previous literature linking agriculture and climate change has examined alternative mitigation strategies in higher-income-countries (Eleto et al., 2015; 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; Thornton et al., 2018). There are few empirical studies on trade-offs between farm-level GHG emissions and farm household welfare (e.g., Paul et al., 2017) or on the potential of productivity improvements to avert trade-offs (Tittonell et al., 2015).

Previous research (Ayinde et al., 2020) examined the farm-level impacts of restrictions on GHG emissions for two types of farms in Northern Nigeria using a farm-level optimization model. In analyses for a single year (2015), we found that limits on GHG emissions would reduce farm household income and modify production patterns, land use and input purchases. Larger required GHG emissions reductions resulted in higher marginal costs in terms of foregone household income. The key contribution of the previous work was to document empirically the nature of whole-farm trade-offs between income and GHG emissions and related effects on land use, input use and labour markets.

One limitation of the analytical approach used in Ayinde et al., (2020) is the analysis of income-GHG emissions trade-offs for only one year. This approach ignores the potential impacts of inter-annual variation that could be important to assess potential GHG emissions reduction strategies and their trade-offs. Given that inter-annual variation in costs, prices and yields are common in smallholder farming systems (Niles & Brown, 2017) consideration of additional years is an appropriate extension of our previous work. Previous studies (Bellarby et al., 2014; York et al., 2017; Tariq et al., 2018) have illustrated the types of methods required and information generated to evaluate inter-annual variation from cross-sectional data. However, these studies have not integrated the knowledge into multiple-product farm-level analyses to assess their fit within specific farming systems.

The main objective of this paper is to assess the impacts of inter-annual variation in input costs, input use, output prices and product yields on the trade-offs between farm income and GHG emissions. Similar to Ayinde et al., (2020) we analyse these trade-offs for two production systems in Nigeria that incorporate trees, grain and legume crops, and multiple livestock species. We compare the impacts of GHG restrictions for five production cycles from 2015/16 to 2019/2020. This multiple-year comparison provides additional insights about the nature of trade-offs under different production and market conditions.

2. Material And Methods

2.1 Geographic Setting and Site Selection

The analysis considers case examples of representative farms in Kano and Jigawa States in Nigeria (Fig. 1). Kano State is the most-extensively irrigated state in the country (NAERLS & FDAE, 2019). Bunkure Local Government Area (LGAs) in Kano State was randomly selected due to the homogeneity of tree, crop and livestock production systems in the LGAs of Kano. Maigateri LGA in Jigawa State was purposively selected as an area with representative current tree, crop and livestock production practices, and due to the large number of livestock and its proximity to Zinder region in the Republic of Niger where successful climate-smart technologies were already established (Abdullahi, 2021; Carsan et al., 2014; Reij & Smaling, 2008). Both LGAs are characterized by numerous smallholder farms that integrate grain (sorghum) and legume crops (soybean and groundnut), trees African Locust Bean (*Parkia biglobosa)* and Camel's Foot (*Piliostigma reticulatum*), and multiple livestock species (cattle, goats and sheep). Sorghum grain and legume seeds are consumed by humans and 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 Farm-level Optimization Model Specification

We assess the trade-offs between income and GHG emissions using an optimization model that maximizes household "full income" (value of production less cash costs for inputs and hired labor (Singh et al., 1986), subject to constraints on land and input-output relationships for trees, crops and livestock. The model represents annual agricultural production activities for the years 2015 to 2019 but with monthly labor requirements for each agricultural activity. Multiple purchased inputs (N fertilizer, urea, seeds and agricultural chemicals) are required for trees and crops, and livestock require feed that meets energy, protein and dry matter requirements. Each agricultural activity also produces multiple outputs; a total of 20 *(j, p)* combinations of activities and sub-products are represented (Appendix A0). This modelling approach assumes that the pattern of production determined by farm households will be affected by relative incentives (relative profitability) to engage in different activities, subject to relevant constraints. Our model is not explicitly intertemporal; we assume that production patterns in each year are largely independent of those in previous years.

The objective function to be maximized is:

$$\mathrm{Z} = \sum_{\mathrm{j}=1}^{3} \sum_{\mathrm{p}=1}^{8} \mathrm{CROPPROD}_{\mathrm{jp}} \bullet \mathrm{CROPPRICE}_{\mathrm{jp}}$$

$$+\sum_{a=1}^{3}\sum_{q=1}^{3}\mathrm{ANPROD}_{aq}\bullet\mathrm{ANPRICE}_{aq}$$

$$-\sum_{a=1}^{3}\sum_{i=1}^{4}\mathrm{INPUTUSE}_{i}\bullet\mathrm{INPRICE}_{i}$$

$$-\sum_{m=1}^{12}\mathrm{WAGE}\bullet\mathrm{HIREDLAB}_{m}$$

Where the subscripts are defined as:

j is crop activity (1 tree species, 2 crops at each location)

p is crop product (grain, bran, hull, fodder, pod, pod valve, branch, trunk)

a is animal activity (3 livestock species: cattle, sheep, goat)

q is animal product (milk, meat, manure)

i is input (N fertilizer, urea, seed, other agricultural chemicals)

m is month of the year

and the variables are defined as:

Z = annual value of all farm production less cash costs

$\mathrm{CROPPROD}_{jp}$ = Annual production of product P from tree or crop activity J

$\mathrm{CROPPRICE}_{jp}$ = Sales price per unit of product P from tree or crop activity J

ANPROD_{aq} = Annual production of product Q from animal species A

$\mathrm{ANPRICE}_{aq}$ = Sales price per unit of product Q from animal species A

$\mathrm{INPUTUSE}_{i}$ = Annual use of purchased input I

$\mathrm{INPRICE}_{i}$ = Purchase price per unit of input I

WAGE = Hourly wage paid to hired labour (same in all months)

$\mathrm{HIREDLAB}_{m}$ = Hours of hired labour in month M

This objective function maximizes the total value of products derived from farm production activities less the costs of hired labour and the value of purchased inputs. The activities that generate revenue for the farm household include trees, sorghum, legumes, cows, goats and sheep, each of which has sub-products used as inputs on the farm or sold (Appendix Table A0). A total of 20 (j, p) combinations of activities and sub-products are represented. Purchased inputs include fertilizer (NPK mix and urea), an aggregation of agricultural chemicals, and seed for grains and legumes.

2.2.1 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:

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

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 produced of product P from tree or crop activity J is equal to the product yield per hectare times the amount 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:

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

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.

2.2.2 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 is modelled because it is the predominant land type used for rain-fed production. The land constraint equation for the farm household was:

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

where

$LAND_j$ = hectares land allocated to production of tree or crop J

HHLAND = total cultivable 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:

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

where

$CROPLAB_{jm}$ = hours labour required in month M for tree or crop activity J

$ANLAB_{am}$ = hours labour required in month M for animal species A

$HHLAB_m$ = hours labour available from the farm household in month M

The monthly hours of labour required equals the labour requirements per unit of land allocated to J time 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.

2.2.3 Input Use Quantities

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

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

Where

$INPUTREQ_{ij}$ = is the requirement of purchased input I per hectare of land used for tree or crop activity J

$INPUTUSE_i$ = Annual total use of input I

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

2.2.4 Animal Nutrient Requirements

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

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

Where

$NUTREQ_{an}$ = the annual requirement for nutrient N (Metabolizable 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

$NUTCONTENT_{jpn}$ = Content of nutrient N per product P from crop or tree type J.

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

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

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

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

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

$DMHIGH_a$ 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 for animal species A but less than a maximum possible annual amount of DM (which is due to rumen fill constraints).

2.2.5 Tree, Crop and Animal Products Balance

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

$INTINPUT_{jp}$ = 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

$MILKCALF_{aq}$ = 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.

2.2.6 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:

$$\sum_{\mathrm{j}=1}^{3} \mathrm{LAND_j} \bullet \mathrm{MANREQ_j} \leq \sum_{\mathrm{a}=1}^{3} \mathrm{ANIMALS_a} \bullet \mathrm{MANURE_a}$$

Where

$MANREQ_j$ = the annual amount of manure (from any animal species) required per hectare of land allocated to crop or tree J

$MANURE_a$ = 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.

2.2.7 GHG Emissions and Restrictions

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

$$\sum_{\mathrm{j}=1}^{3} \mathrm{LAND_j} \bullet \mathrm{GHGCROP_j} + \sum_{\mathrm{a}=1}^{3} \mathrm{ANIMALS_a} \bullet \mathrm{GHGANIMAL_a} = \mathrm{TOTGHG}$$

Where

$GHGCROP_j$ is 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 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.)

$GHGANIMAL_a$ is the annual GHG emissions in CO_2 equivalents per animal of type A

TOTGHG is 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 in CO_2 equivalents allowed from the farm

The value of GHGLIMIT is modified in our scenarios to assess the impact on the objective function.

2.3 Data

The data to specify the parameters required for the optimization model were derived from both primary and secondary sources. Primary data were obtained from a purposive sample using Participatory Rural Appraisal (PRA) in form of Focus Group Discussions (FGD) for the base year 2015 in Maigateri and Bunkure LGA, respectively. A subsequent small-scale household survey and key informant interview was administered to a random sample of farm households in Maigatari and Bunkure during the 2015 and then extended for the production seasons from 2016 to 2019. The FGD, household survey and key informant interview (cited collectively as “field survey data” below) provided basic information about the characteristics of households and their farming systems. 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 8 Locust Bean (*Parkia Biglobosa*) trees in Bunkure and sorghum/groundnut cultivation beneath 6 trees of Camel’s Foot (*Piliostigma reticulatum*) trees in Maigateri LGA. The secondary data provided input requirements, product outputs and GHG emissions.

2.3.1 Tree Data

The data required for tree include the annual yields of the Locust Bean and Carmel’s Foot products, prices of outputs, inputs used in tree production and input prices from 2015 to 2019 in Bunkure and Maigatari, LGA in Appendix Table A1. An average tree number of 6 trees/ha was reported by sampled farmers during the base year study in 2015. Biomass output from trees, hedges and woodlot from trees in Sudano–

Sahelian savannahs was estimated to be between 2.5- 3 m^3/ha/year (AERLS/ ABU, 1988) with per capita fuel wood consumption of between 0.75- 1.0 m^3/day (Stéphenne & Lambin, 2001). Fodder yield are between 10–12% of woodlot. Yield per ha of Locust Beans pod is between 350–500 kg/hectare and daily/capita consumption of locust-bean pod is between 1-17g (NRC, 2006). Values were converted to kilograms with mass obtained using conversion-factor of 750 kg/ m^3 (CTFT, 1989 cited in Stéphenne & Lambin, 2001). We assumed yields 50% of those Locust Bean based on comparison of information about the two specifies from the Plant Use English (https://uses.plantnet-project.org/en/Main_Page). Yields of subsequent years from 2016 to 2019 at both sites were assumed to have reduced by a factor of 0.5. The 0.5 are assumed values based on Hamer et al. 2007 report of an average area decline of most fodder in Segou region of Mali by 56% cited in (Bayala et al., 2014).

2.3.2 Crop Data

Yield data derived from field surveys complemented with published literature related to the use of by-products from sorghum and soybean/groundnut production in livestock production were derived using formula for harvest index in Powell et al., (1995) and Bayala et al., (2014) from 2015 to 2019 in Bunkure and Maigatari, LGA in Appendix Table A2 and A3. Input requirements and input and output prices were derived from field survey data complemented for Nitrogen fertilizer by valuation relationships from previous literature and published sources (NAERLS & FDAE, 2014; 2016; 2017; 2018; 2019).

2.3.3 Livestock Data

The cattle, sheep and goat specific data required for modelling include the weight, average dry matter (DM) intake, yields of products and output prices in from 2015 to 2019 in Bunkure and Maigatari, LGA (Appendix Tables A4 to A6). This information was derived from field survey data complemented with relevant literature (Dupriez & De Leener, 1998; FAO, 1998; Otte & Chilonda, 2002; Teye & Sunkwa, 2010). Manure production per animal was estimated based on Teenstra et al., (2015) for cattle and the Small Ruminant Nutrition System (SRNS: https://www.nutritionmodels.com) for sheep and goats.

Additional data are required on the nutritional value of the plant products used to feed livestock. These data comprise the dry matter (DM), energy and protein content of fodder and by-products from trees, sorghum and the two legume crops. Data on DM, Metabolisable energy (ME) and Crude protein (CP) were obtained from feed composition tables in Feedipedia (https://www.feedipedia.org) and Dupriez & 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 3. 5% for sheep and goat. Per-animal ME requirements were 45.2 Mega joules of Metabolization Energy /day (MJ ME/day) for cow producing less than 5 litres/day from FAO, (1998) and 3.95 MJ ME/day for maintenance of sheep and goat from SRNS. Crude protein requirements for cattle were 0.43 kg/animal/day (for maintenance, growth and milk production) from FAO, (1998) and 0.04 kg/animal/day for sheep and goats based on animal characteristics from the field survey and requirements data from SRNS.

2.3.4 GHG emissions data

Tier 1 default equations, methods and emission factors (EF) from IPCC, (2006) guidelines were used to estimate GHG emissions based on data describing current tree, crop and livestock production systems in the region. The Tier 1 default method was used due lack of robust site-specific empirical measurements. Our principal focus was on production practices that entailed the use of urea and nitrogen fertiliser inputs in managed soils as well as farming practices that involve burning of bushes and crop residues. Values of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), nitrogen oxides (NOx) and carbon monoxide (CO) from burning were calculated using biomass burned (0.01 tonnes DM/ha) multiplied by the applicable EF. Other emissions considered for estimation include methane (CH_4) emissions from enteric fermentation and manure management of ruminant livestock that include sheep, goat and mature cows grazing on large areas.

The nitrous oxide (N_2O) emissions from soils analysed in our study include direct N emissions from nitrite (NO_3), ammonia (NH_3), and nitrous oxide (N_2O) from manure, tree and crop residues and fertiliser. In addition to indirect Nitrous oxide (N_2O) emissions from manure management system (MMS) and managed soil (MS). CO_2 emissions from urea fertilisation was estimated using Tier 1 default EF of 0.20, that corresponds to 20% for CO $(NH_2)_2$. The EFs for developing countries were used to compute livestock-related methane emissions. All nitrous oxide and methane (CH_4) emissions were converted to CO_2 equivalents (100-year global warming potential) by using a multiplier of 310 and 21, respectively from the IPCC, (2007).

2.4 Scenarios analysed

A Baseline scenario representing current production patterns was developed and subsequently evaluated to see how production activities and household income would be modified subject to reductions in GHG emissions.

Two scenarios were developed in addition to the baseline for each location:

- 10% reduction in GHG emissions compared to the Baseline
- Maximum allowable reductions in GHG emissions for Bunkure and Maigateri LGAs consistent with maintaining minimum household consumption requirements for tree, crop, animal products and purchased and owned inputs used.

3 Results

As expected, inter-annual variations in input and output prices, input requirements and yields result in differing income-maximizing patterns of production, income and GHG emissions for both of the LGAs (Figure 2; Appendix Tables A7 and A8) in our Baseline scenarios. Baseline production patterns were similar across years (in part due to assumed minimum household consumption requirements), with coefficient of variation (CV; standard deviation divided by mean) values generally less than 0.2. Incomes were more variable across years in both LGA, with CV values of 0.32 and 0.15 in Bunkure and Maigateri, respectively. GHG emissions showed less variability than either incomes or production patterns, with CV values of 0.06. The variation in both incomes and GHG emissions was larger in Bunkure due to larger changes in yields and output prices[1]. Higher Baseline GHG emissions for the Maigatari LGA imply greater scope for lower GHG in the analysis of scenarios requiring reductions.

There are many outputs that could be reported from the analysis of GHG emission reductions, but our focus is on changes in full income and GHG emissions per farm per year from 2015 to 2019. For each of the two LGAs, there exists a substantive trade-off between household income and GHG emissions reduction, but the underlying changes in production patterns and values of the trade-offs differ in the two areas given their Baseline production patterns and input usage. These trade-offs can be represented as cost curves that describe the increased cost (in terms of farm income reductions) to achieve a given or maximum level of annual GHG emissions reductions (Figures 3 and 4). In these graphs, the point (0, 0) represents Baseline (i.e., no change from Baseline income or GHG emissions) and the other points depict changes in income associated with allowable reductions in each of the years.

For both LGA and for all years, there is a pattern of increased costs to achieve larger GHG emissions reductions (Figures 3 and 4). In Bunkure, a 10% reduction in GHG emissions would result in a small (2%) mean reduction in income but the mean maximum possible reduction of 16% resulted in a mean income decrease of 22% for the five years analysed. For Maigatari, in contrast, a 10% reduction incurred a mean reduction in income of 12.5% across the five years studied. The mean maximum reduction in Maigatari was 23%, which incurred a mean average reduction in income of nearly 35%. Despite similarities, the patterns of cost changes incurred to achieve GHG emissions in Bunkure differs from Maigatari in three important respects. First, the allowable range of reductions in GHG is smaller for Bunkure, due in part to more limited initial cattle holdings and thus smaller Baseline GHG emissions. Second, for three of the years analysed for Bunkure, there are relatively low costs for 10% reductions in emissions, but costs increased markedly to achieve the maximum possible reductions (Figure 3). The pattern in Maigatari shows a more linear response of income reductions with GHG reductions (Figure 4), although costs increase more rapidly beyond 10% for the year 2015. Finally, for Bunkure, reductions of 10% were not possible in two of the years (2018 and 2019) because the patterns of production (e.g., smaller numbers of animals) resulted in relatively low initial values of GHG emissions and thus smaller feasible reductions. In those two years, the maximum possible reductions in GHG emissions were 9.4% and 3.7%, respectively.

[1] For example, the model results for income are quite sensitive to the assumed value of the output price for Locust Bean pods, which was reported to have increased from 1000 Naira/kg in 2018 to 1200 Naira/kg in 2019.

4 Discussion

Our findings regarding the impacts on farming systems required to reduce GHG emissions are similar to those from our previous work Ayinde et al., (2020): changes in production patterns result in lower income, less purchased input and hired labour use, and reductions in the marginal value of land (Appendix Tables

A7 and A8). A key adjustment is the reduction in animal numbers, given that the proportion from livestock often accounted for about two-thirds of total GHG emissions. Reduced livestock production also affects incomes given that prices for animal products are high relative to crops products. This effect arises due to higher GHG emissions per unit of product from livestock (ILRI, 2006; Havlı´k et al., 2014; Herrero et al., 2014).

Changes in production patterns are key drivers of changes in the Baseline scenario incomes and GHG emissions, which serve as a starting point in our analysis. Optimal production changes in response to both the relative profitability (revenues less cash costs) of the different activities in addition to the feasibility of production. A key interaction exists between feed production and animal nutrient requirements that constrains production patterns. We assume that cattle nutritional needs must be met from available farm resources (i.e., tree products and by-products of crop production). As the yields of crops vary over time, this has a substantive effect on the number of animals that can be maintained, and this effect is particularly strong for the yields of products derived from the tree species. For example, only small GHG reductions were possible in Bunkure in 2018 and 2019. The principal reason was the reduction in the yields of Locust Bean products (fodder, pod valves and bran) over time from 2015 to 2019 as reported by Hamer et al. (2007) cited in Bayala et al., (2014).

Other than the general results that income-GHG emissions trade-offs exist and that reductions in animal numbers are prioritised to achieve GHG reductions, a key point is that the feasible reductions in GHG emissions and the impacts on other production system components are both site-specific and time-variable. These spatial and temporal variations thus would be important to the design of any program to provide appropriate incentives to smallholder farmers in these regions to reduce GHG emissions. Both the amount of GHG reductions that are feasible while maintaining household consumption patterns and the impacts of income will vary by location and with inter-annual variation in yields and prices[2], changes with can be difficult to predict with a high degree of accuracy *ex ante*. To be more consistently feasible, GHG emissions reductions targets would likely need to be considerably less than the maximum percentage reductions evaluated in our study—and in some years the feasible reduction may be considerably less than 10% (as for Bunkure in 2019).

[2] And here we consider mean yields and output prices, not more extreme production and marketing conditions that could occur under drought.

5 Conclusions And Implications

Our analyses show an explicit representation of the impacts on income-GHG emissions trade-offs of inter-annual variation in yields, cost of farm products and prices of inputs. Similar to previous work, we find that in the absence of productivity-enhancing technologies or practices, reductions in GHG emissions on the farms in these two LGA would require reductions in household income, changes in productions patterns and reductions in input use. We also note that a key adjustment is a reduction the number of livestock. However, our evaluation of different years and locations suggests that the empirical values of trade-offs will vary due to both these considerations, making more complex the design of any program to offer incentives (i.e., to compensate) farmers for reductions.

Although our analyses suggest the usefulness of including multiple years and locations in an analysis of income-GHG trade-offs, a number of extensions would be appropriate. First, we did not consider the extent to which productivity-enhancing technologies could mitigate income-GHG emissions trade-offs. Previous literature (van Loon et al., 2019) has suggested that increased yields could allow for reduction in per-unit GHG emissions, but assessment at the farm level would require scaled-up adoption of new varieties or practices to be feasible but should also include consideration of impacts on other elements of the production pattern (e.g., shifts in the amounts of other crop production and livestock numbers). Moreover, analytical methods that represent more explicitly the inter-temporal dynamics of production and GHG emissions (e.g., Stephens et al., 2012) may help to refine the nature of the trade-offs described on a yearly basis in our current analyses. Finally, development of data to support more sophisticated assessments of GHG emissions (i.e., rather than Tier 1) from agricultural activities will help to refine the assessment of trade-offs and the identification of potential win-win technologies.

Our analyses suggest that reductions in GHG emissions would require compensatory payments to avoid placing the financial burden of reducing GHG emissions on the region's smallholder farmers. Such payments may necessitate both funding support and administrative resources and capacity to be implemented effectively. Training and resources to provide information on the best means of reducing emissions, receiving payments, or integrating new practices into farming systems are important areas for research and development and policy recommendations. There are currently no substantive policy proposals to the best of our knowledge at the study sites that would require GHG reductions by smallholders. However, as efforts to reduce GHG emissions accelerate, the information provided by this and similar studies may take on additional importance.

Declarations

Ethical Approval: All due consent have been sought.

Consent to Participate: All due consent have been sought.

Consent to Publish: All due consent have been sought.

Authors Contributions: All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Taiwo Ayinde], [Charles F. Nicholson] and [Benjamin Ahmed]. The first draft of the manuscript was written by [Taiwo Ayinde] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Competing Interests: The authors declare no competing interests.

Availability of data and materials: All data, materials and software application used for the study conformed to standard practise

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Figures

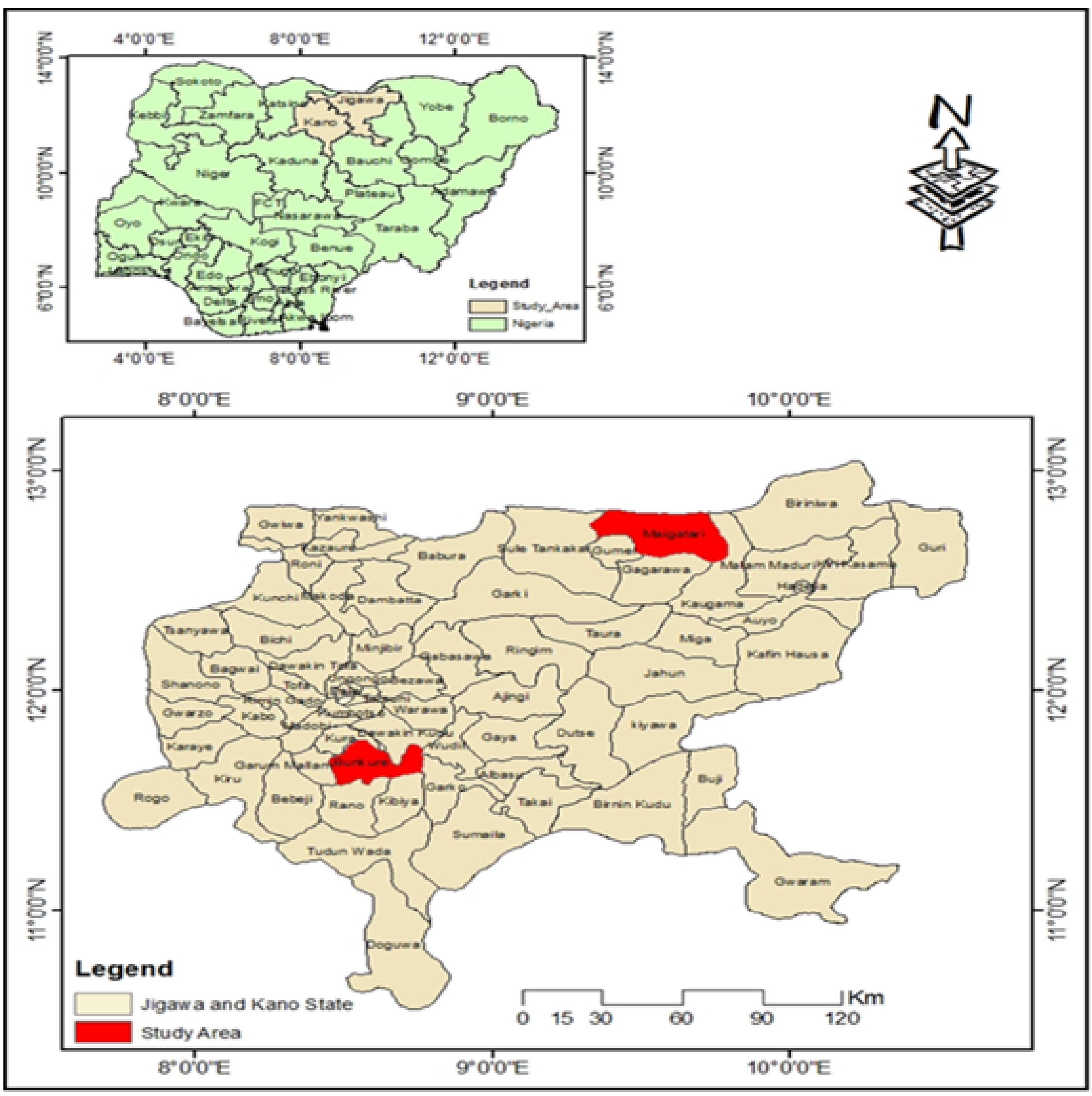

Figure 1

Locations of the Study Sites Maigateri in Jigawa State and Bunkure in Kano State

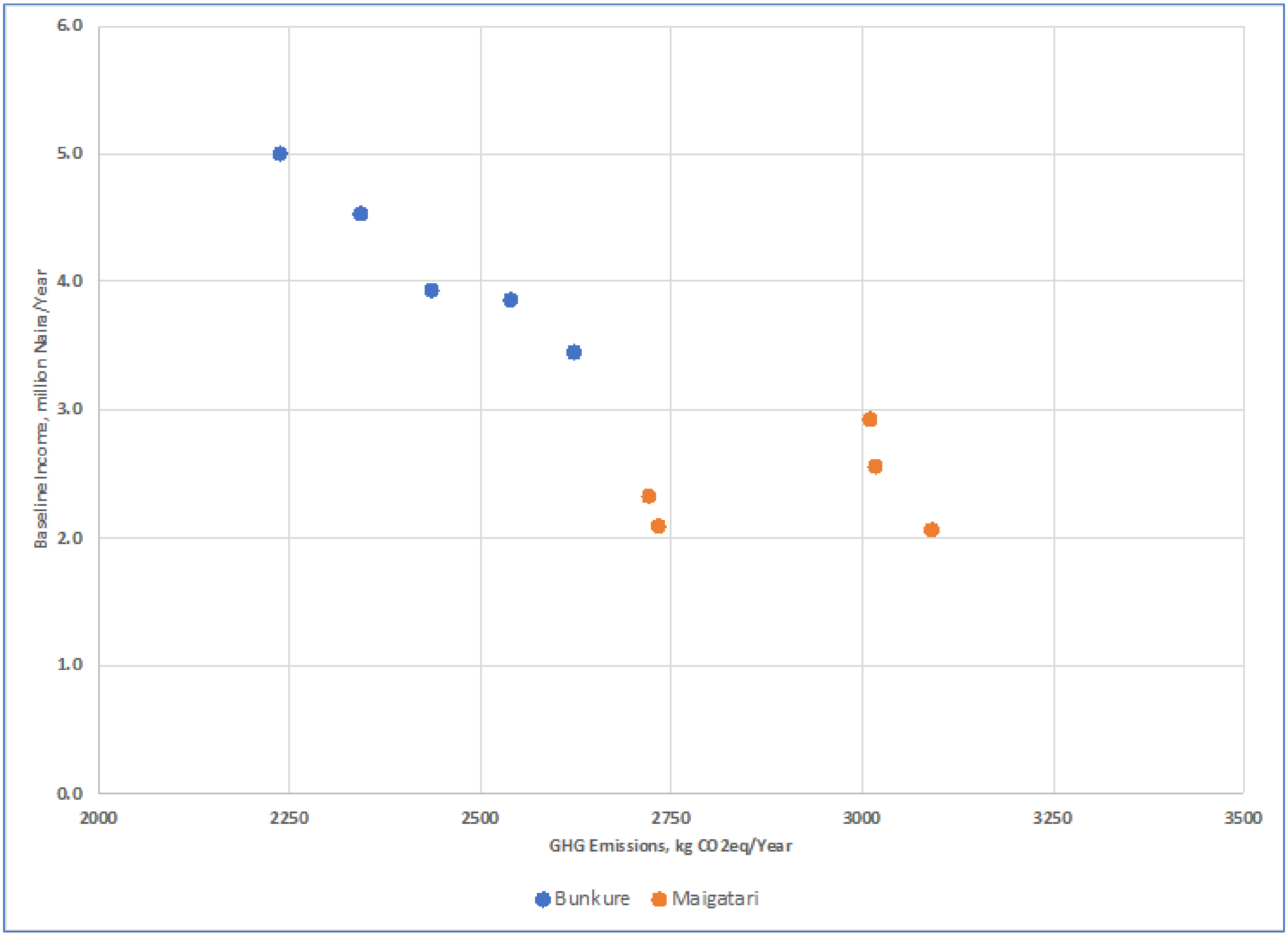

Figure 2

Variation in Baseline Income and GHG Emissions, Bunkure and Maigatari LGA, for Analysed Years 2015 to 2019

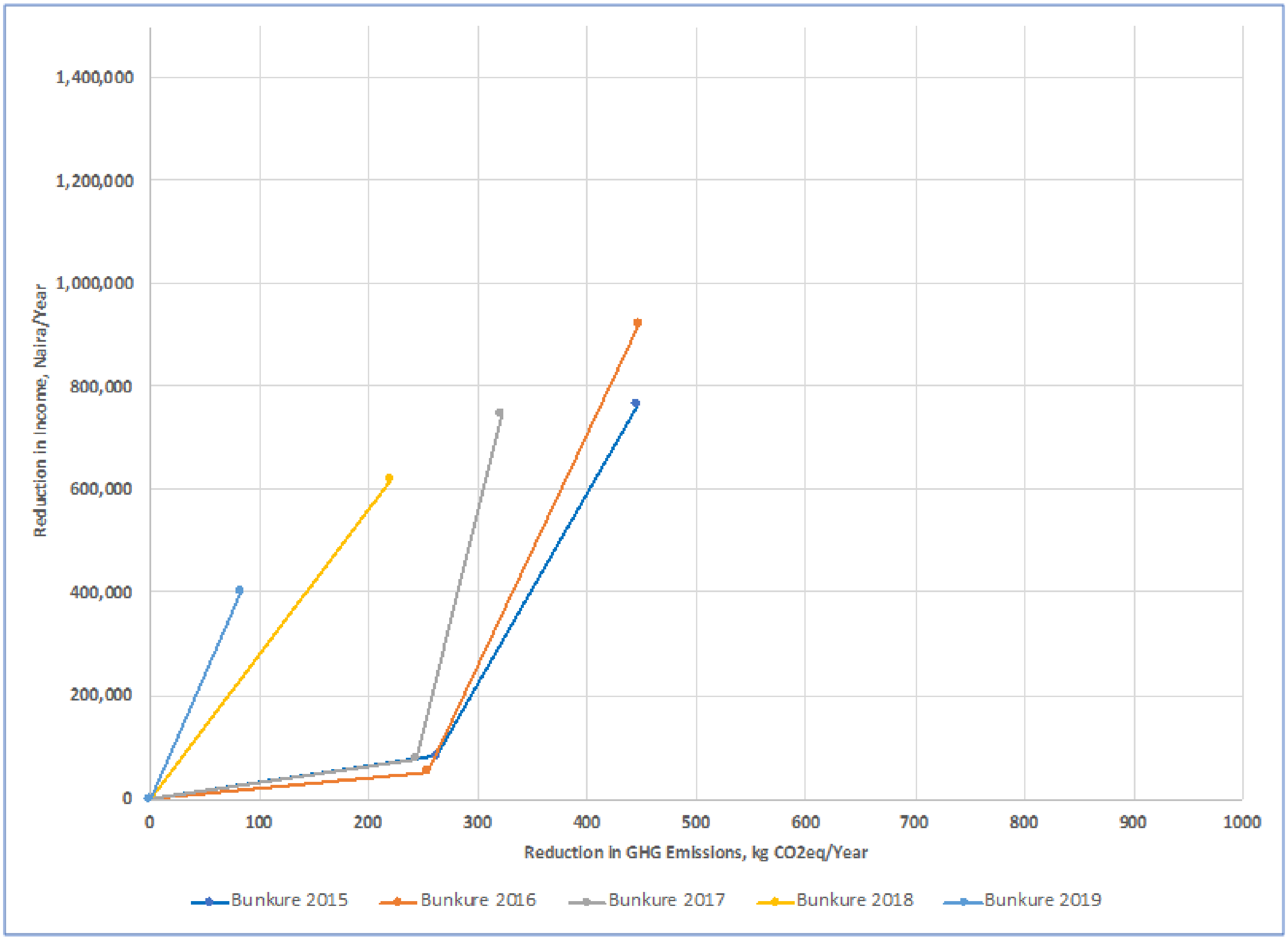

Figure 3

Marginal cost (foregone income) for GHG emission reductions for Bunkure LGA, production years 2015 to 2019

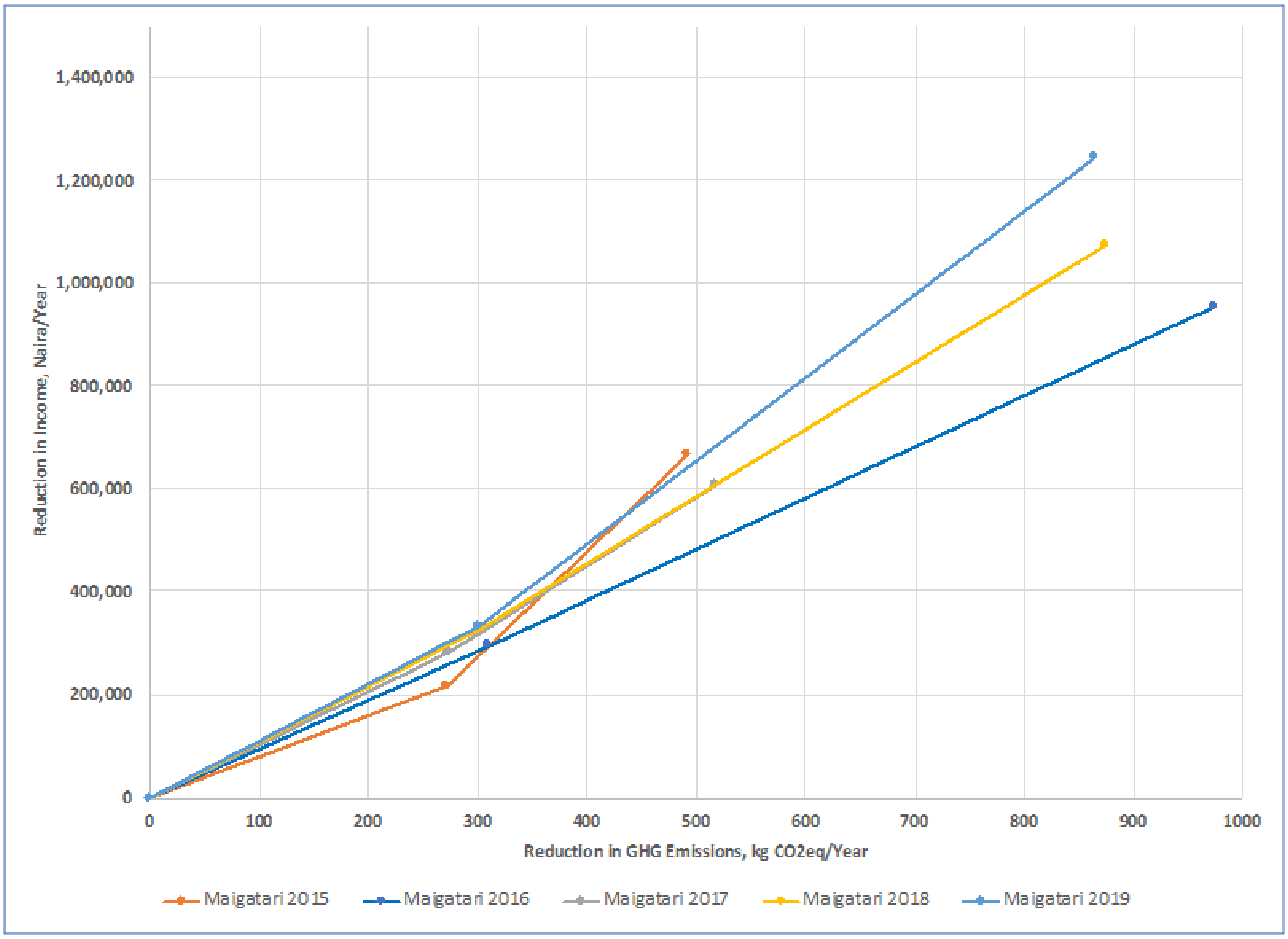

Figure 4

Marginal cost (foregone income) for GHG emission reductions for Maigatari LGA, production years 2015 to 2019

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