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Agricultural intensification scenarios, household food availability and greenhouse gas emissions in Rwanda: Ex-ante impacts and trade-offs

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A B S T R A C T

Rwanda's agricultural sector is facing severe challenges of increasing environmental degradation, resulting in declining productivity. The problem is likely to be further aggravated by the growing population pressure. A viable pathway is climate smart agriculture, aiming at the triple win of improving food security and climate change adaptation, while contributing to mitigation if possible. The Government of Rwanda has initiated ambitious policies and programs aiming at low emission agricultural development. Crop focused policies include the Crop Intensification Program (CIP) which facilitates access to inorganic fertilizer and improved seeds. In the livestock subsector, zero-grazing and improved livestock feeding are encouraged, and the Girinka program provides poor farm households with a crossbred dairy cow. In this study, we aimed at assessing the potential impact of these policy programs on food availability and greenhouse gas (GHG) emissions of 884 households across different agro-ecologies and farming systems in Rwanda. Household level calculations were used to assess the contribution of current crops, livestock and off-farm activities to food availability and GHG emissions. Across all sites, 46% of households were below the 2500 kcal MAE^{-1} yr^{-1} line, with lower food availability in the Southern and Eastern Rwanda. Consumed and sold food crops were the mainstay of food availability, contributing between 81.2% (low FA class) to 53.1% (high FA class). Livestock and off-farm income were the most important pathways to higher FA. Baseline GHG emissions were low, ranging between 395 and 1506 kg CO_2e hh^{-1} yr^{-1} per site, and livestock related emissions from enteric fermentation (47.6–48.9%) and manure (26.7–31.8%) were the largest contributors to total GHG emissions across sites and FA classes. GHG emissions increased with FA, with 50% of the total GHG being emitted by 22% of the households with the highest FA scores. Scenario assessment of the three policy options showed strong differences in potential impacts: Girinka only reached one third of the household population, but acted highly pro-poor by decreasing the households below the 2500 kcal MAE^{-1} yr^{-1} line from 46% to 35%. However, Girinka also increased GHG by 1174 kg CO_2e hh^{-1} yr^{-1}, and can therefore not be considered climate-smart. Improved livestock feeding was the least equitable strategy, decreasing food insufficient households by only 3%. However, it increased median FA by 755 kcal MAE^{-1} yr^{-1} at a small GHG increase (50 kg CO_2e hh^{-1} yr^{-1}). Therefore, it is a promising option to reach the CSA triple win. Crop and soil improvement resulted in the smallest increase in median FA (FA by 755 kcal MAE^{-1} yr^{-1}), and decreasing the proportion of households below 2500 kcal MAE^{-1} yr^{-1} by 6%. This came only at minimal increase in GHG emissions (23 kg CO_2e hh^{-1} yr^{-1}). All policy programs had different potential impacts and trade-offs on different sections of the farm household population. Quick calculations like the ones presented in this study can assist in policy dialogue and stakeholder engagement to better select and prioritize policies and development programs, despite the complexity of its impacts and trade-offs.

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1. Introduction

Agriculture is the backbone of Rwanda's economy, involving > 80% of the population, and contributing 30% to the country's GDP. In Rwanda's Vision 2020, agriculture is considered one of the major potential catalysts for employment creation and transformative growth (MINECOFIN, 2000). 46.3% of the country's total land area (2.6 million ha) is arable, and main crops include beans, cassava, wheat, maize and rice. Permanent crops such as citrus, coffee and rubber, flowering shrubs, fruit trees, nut trees and vines occupy 9.5% of country's surface (NISR, 2014). However, Rwanda's agricultural sector is facing challenges of increasing environmental degradation, resulting in declining productivity. 34% of surveyed households said they are facing problems caused by environmental degradation, with erosion, reduced agricultural production and destructive rains being mentioned most often (NISR, 2011). The problem would be further aggravated by the growing population. If the current population growth rate of 2.8% sustains, Rwanda will reach 26 million inhabitants by 2050, translating to a population pressure of 1000 people per km^2.

Globally, agriculture is a principal source of climate change, directly contributing 14% of anthropogenic greenhouse gas (GHG) emissions, and another 17% through land use change. The majority of future increases in agricultural emissions are expected to take place in low- to middle-income countries (Smith et al., 2007). While industrialized countries have to dramatically reduce current levels of GHG emissions, developing countries face the challenge of finding alternative, low carbon development pathways. Climate-smart agriculture (CSA) is seen as one of these pathways, aiming at transforming agricultural systems towards the triple win of increased food security, climate change adaptation, and mitigation. However, it has been recognized that in developing countries, mitigation should be considered as co-benefit while priority lies with food security and adaptation (Lipper et al., 2014; Campbell et al., 2014). CSA is complementary with sustainable intensification (SI), which aims at increasing agricultural productivity from existing agricultural land while lowering its environmental impact. Increased resource use efficiency contributes to SI as well as CSA through increased productivity and reduced GHG emissions per unit output (Campbell et al., 2014). CSA and SI both acknowledge the importance of potential trade-offs between agricultural production and environmental integrity. A better understanding of these trade-offs is needed to reach a more productive and sustainable agricultural sector (Klapwijk et al., 2014a; Steenwerth et al., 2014; Kanter et al., 2016).

The government of Rwanda has recognized the dual challenge of food security and environmental sustainability, and has therefore put emphasis on generating an integrated suite of agricultural and environmental strategies, policies, institutions and funds. The Strategic Plans for the Transformation of Agriculture (PSTA-III, 2014–2017) (MINAGRI, 2009a) and Rwanda's Vision 2020 (MINECOFIN, 2000) are designed to guide the fundamental transformation of Rwanda into a middle income country by 2020. One of the six pillars of Vision 2020 is a Productive and Market Oriented Agriculture, with Sustainable Natural Resource Management as cross-cutting theme (MINECOFIN, 2000). The cross-sector national strategy on Green Growth and Climate Resilience adds the environmental dimension, calling to address poverty and climate change concurrently (MINIRENA, 2011). Well-known agricultural policy programs aiming to implement the strategic aspirations are the Crop Improvement Program (CIP), which supports access to mineral fertilizer and improved seeds (MINAGRI, 2011); the Girinka program which provides crossbred cows to poor farmers under a pass-on system of payment and wealth transfer (MINAGRI, 2006); and the strategy for animal nutrition improvement which calls for adequate on-farm mix of forage legumes and grasses and concentrate feeds under zero grazing (MINAGRI, 2009b).

Ex-ante impact assessment can help decision makers in targeting and upscaling technological interventions. Farm household models have often been used for this purpose, although integrated analyses of food security at household level are still scarce (Van Wijk et al., 2014). A standard approach is to capture the diversity of farming systems with a limited number of farm types, often using resource endowment or production goals as clustering factors (e.g. Tittonell et al., 2010). Potential impacts are quantified for these farm types, and scaled up to population level by using information on the relative importance of each type. This study takes an alternative approach to assess potential impacts of policy oriented scenarios on food availability and GHG emissions across different agro-ecologies in Rwanda. Instead of focusing on few representative farm types, we apply relatively quick and simple calculations across a large number of households. The objectives of this study are therefore to i) quantify the baseline contribution of crops, livestock and off-farm activities to household food availability and GHG; ii) assess differences in contributions within and between locations and food availability classes; iii) and determine the impact, synergies and trade-offs of crop and livestock intensification policies on food availability and GHG.

2. Materials and methods

2.1. Baseline household survey and study sites

A household survey was conducted in June – December 2006 by the Consortium for Improvement of Agriculture-based Livelihoods in Central Africa (CIALCA) in Rwanda, DR Congo, and Burundi. In Rwanda, 911 households were surveyed across different administrative units and agro-ecologies (Fig. 1). The Birunga and Congo Nile Watershed Divide (CNWD) are highland areas between 1900 and 2500 m, with abundant rainfall, highly weathered soils, and expansive forest cover. The Bubereka highlands are a plateau at 2300 m altitude, and soils are generally more fertile than in the CNWD. The Central Plateau is a large region of hills and valleys of an average altitude of 1700 m and annual rainfall of 1200 mm, and its soils are suitable for a wide range of crops. The Eastern Plateau & Peripheral Bugesera are the extension of the Central Plateau into the drier East, with a hilly topography and moderate agricultural potential. The Eastern Savanna & Central Bugesera include the lowlands in the East (1250–1600 m) with 850–1000 mm annual rainfall, and the agricultural potential is lower. The Imbo area is characterized by high temperatures, abundant rainfall, good quality alluvial soils and possibilities for irrigation, which makes it conducive for intensive agriculture (Fig. 1; Verdoodt and Ranst, 2003). The survey collected quantitative information on the socio-economic status of households, agronomic characteristics of the farming system, market access and commercialization of crops, food security status and nutrition, and health of the household members (Ouma et al., 2012). 27 outliers were excluded from the analysis due to unrealistic fertilizer and crop production values, or missing crop land area data. The final database contained data of 884 households: 190 households in Bugesera, 200 in Kirehe, 196 in Nyagatare (all Eastern Province), 99 in Karongi, 50 in Rubavu, 50 in Rusizi (all Western Province), and 99 in Ruhango (Southern Province).

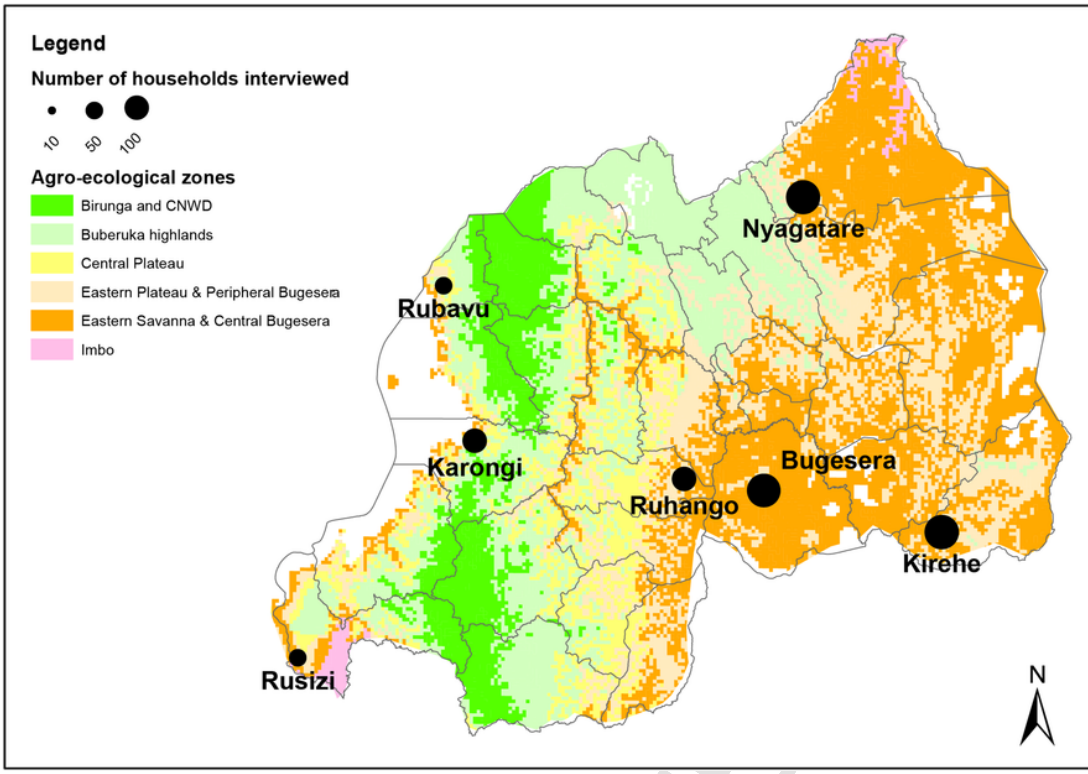

Fig. 1. Map of household survey sites across agro-ecological zones in Rwanda. The map is based on Verdoodt and Ranst (2003). See Materials & methods (2.1) for a description of the zones which differ in altitude, rainfall and soil properties.

2.2. Food availability calculation

Food security encompasses various dimensions including food availability, food access, food utilization and food stability. Food availability in general refers to both caloric intake as well as nutritional requirements (Carletto et al., 2013a). In this study, we used a simple proxy for food security, which exclusively focusses on the energy component of food availability. The food availability (FA) indicator was developed from initial work by Hengsdijk et al. (2014), and first published by Frelat et al. (2016) who calculated FA for > 13,000 households across sub-Sahara Africa. Ritzema et al. (2016) applied it to data from 1800 households in West and East Africa, illustrating its usefulness for potential impact assessment. FA is a potential supply indicator, representing the daily food energy availability per household member from consumption of farm produce and food purchases with on-farm and off-farm income. The FA indicator does not intend to fully account for all household expenses or nutritional requirements. For this study, seven livelihood components were delineated that contribute to FA within and across sites: food crop products (consumed and sold), cash crop products, livestock products (cattle, sheep and goats, poultry), and off-farm income (Fig. 2a).

FA is expressed in Potential Food Equivalent energy in kcal (*PFE energy*) per capita per day and is calculated as

$$PFE = \frac{E_{cons} + E_{income}}{365 \times n_{hh}} \tag{1}$$

where E_{cons} is the direct consumption of the *PFE energy* from on farm food produce in kcal (calculated from Eq. (2)), E_{income} is the indirect consumption of the PFE energy from income (farm sales, off farm) in kcal (calculated from Eq. (3)) and n_{hh} is the household size in Male Adult Equivalent (MAE; see Eq. (5)).

The *PFE energy* from direct consumption of on farm produce is calculated as

$$\mathrm{E_{cons}} = \sum_{c} \mathrm{E_c} \times \mathrm{m_c} \times \theta_c + \sum_{l} \mathrm{E_l} \times \mathrm{m_l} \times \theta_l \tag{2}$$

where E_c is the energy content of the yield of crop c, m_c is the yield of crop *c* in kg, and θ_c is the percentage of the yield of crop *c* consumed. For livestock E_l is the energy content of livestock product *l*, m_l is the produced amount of product *l* in kg, and θ_l is the percentage of livestock produce *l* consumed. Energy contents were based on a standard product list developed by the US Department of Agriculture USDA (source: http://ndb.nal.usda.gov/ndb/search/list).

The *PFE energy* from indirect consumption of food purchased with income is calculated as

$$E_{income} = I_{USD} \times \frac{E_{staple}}{P_{staple}} \tag{3}$$

I_{usd} is the money earned by the household (by selling farm production and off farm income) in USD (calculated from Eq. (4)), E_{staple} is the PFE energy content of the staple crop (kcal/kg), P_{staple} is the price per kg of the staple crop (USD/kg).

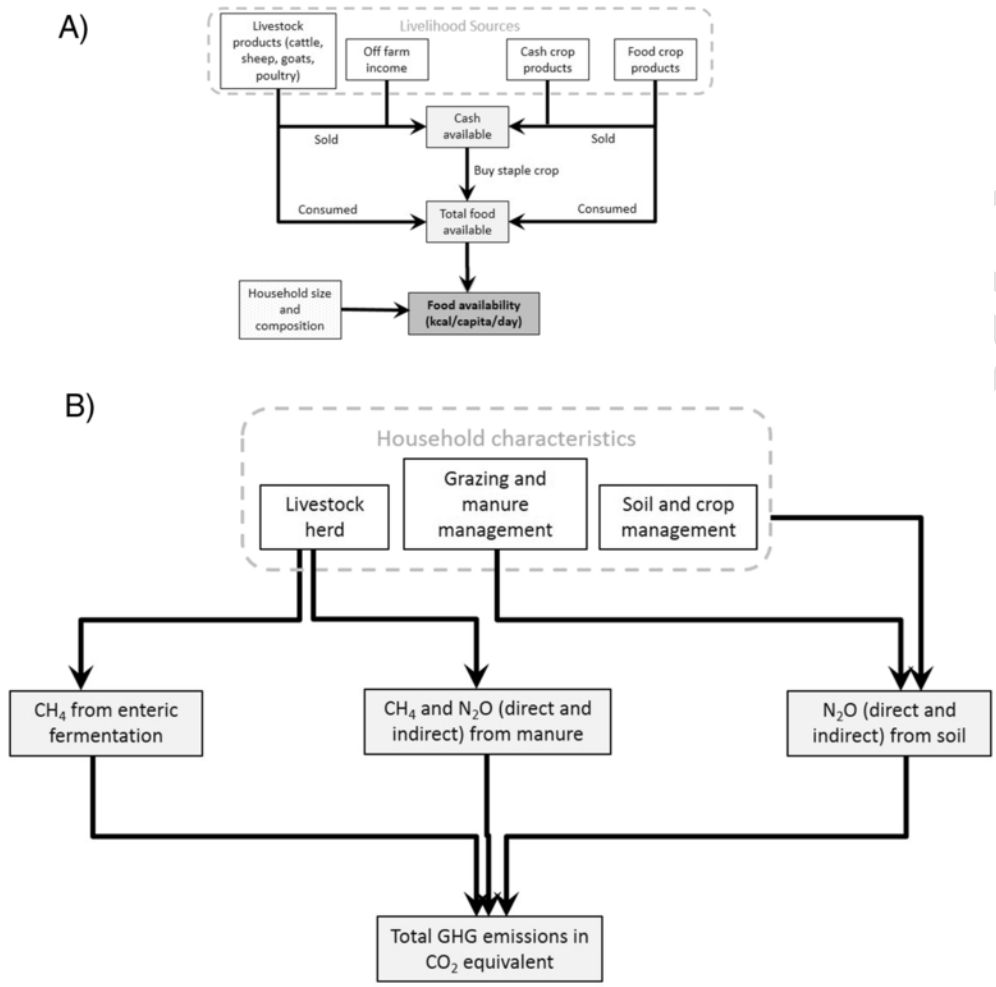

Fig. 2. (a) Schematic representation of the FA calculations at household level in energy (kcal) MAE^{-1} day^{-1}, adapted from Frelat et al. (2016); (b) Schematic representation of GHG calculations at household level in CH4 and N2O from enteric fermentation, manure and soil emissions, converted to CO2e in the sum.

The income earned by the household is calculated as

$$I_{USD} = \sum_{c} P_c \times m_c \times (1 - \theta_c) + \sum_{l} P_l \times m_l \times (1 - \theta_l) + \Phi \tag{4}$$

where P_c and P_l are the price of the crop yield c or livestock product l in $USD \cdot kg^{-1}$, and Φ is the off farm income (in USD).

Household members were disaggregated by gender and age brackets following FAO (2011) to quantify household size in Male Adult Male Equivalents (MAE), based on energy requirements for members of each age bracket

$$n_{hh} = \sum_{i} n_i \times \alpha_i \tag{5}$$

where n_i is number of person in class I, and α_i: percentage of energy requirement of class I (compare to the average energy requirement of a male adult, 2500 kcal per day).

The annual production of crops and their use (consumption and sale) were reported by farmers. Cash crops were defined as crops of which > 90% of the annual produce is sold. Median price values per crop were used, thus all households were assumed to sell crops at the same price. The survey results showed that beans were the main staple crop in the area, having an energy content of 3400 kcal/kg (E_{staple} in Eq. (3)) and a national price of 0.27 USD/kg (P_{staple} in Eq. (3)). Production and consumption of livestock products were not reported in the survey. Instead, we used average production and off-take numbers from Frelat et al. (2016) to estimate milk, meat and egg production per livestock head and year: cattle meat 0.875 kg (local breed and crossbred); cow milk 340 l (local breed); 680 l (brossbred); sheep and goat milk 0.3 l (local breed and crossbred); sheep and goat meat 1.250 kg (local breed and crossbred); poultry eggs 0.9 kg; and poultry meat 0.375 kg. 50% of all livestock produce is assumed to be sold, 50% to be consumed. It is further assumed that households use the income generated from sales of farm produce or off-farm activities to first cover their reported expenses of crop production, and then to purchase the main staple crop beans. Due to lack of reliable data, other household expenses, e.g. for school fees, clothes, or medicine, are not taken into account.

The FA calculation was applied to all 884 households individually. Three FA classes were defined, following Frelat et al. (2016) who showed that the base level of food crop consumption was 1500 kcal MAE^{-1} day^{-1}, while the overall median of FA was roughly 4000 kcal MAE^{-1} day^{-1}. Households with

< 1500 kcal MAE^{-1} day^{-1} were deemed to have insufficient food available ('low FA class'); households with 1500–4000 kcal MAE^{-1} day^{-1} were considered to have sufficient food available ('medium FA class'); and households with > 4000 kcal MAE^{-1} day^{-1} were seen as having more than sufficient food available ('high FA class'). Results were reported in three different ways: a) FA per individual household (kcal MAE^{-1} day^{-1}) with percentage of households below the 2500 kcal MAE^{-1} day^{-1} line (average energy requirement of a male adult); b) median FA (kcal MAE^{-1} day^{-1}) per site and/or per FA class; c) contributions (%) of crop, livestock and off-farm activities to FA.

2.3. Calculation of greenhouse gas emissions

The International Panel on Climate Change (IPCC) guidelines contain the most widely accepted scientific methods to quantify GHG emissions. They are divided in hierarchical Tiers (1, 2, 3) according to methodological complexity and data requirements (IPCC, 2006). The IPCC guideline calculations have previously been used to calculate whole-farm GHG emissions using smallholder household survey data, for example by Seebauer (2014) in Kenya. Fig. 2b provides an overview of household data used and emission sources considered. Given the limited household data available in this study, the GHG emission calculations followed Tier 1 guidelines for emissions from manure (CH_4 and direct and indirect N_2O) and soils (direct and indirect N_2O). Fertilizer quantities were not directly recorded in the survey, so fertilizer application rates were calculated from annual fertilizer expenses per household, using a cost of 2.4 USD per kg N from 2006. Emissions from manure were calculated using default N excretion rates per livestock species and body weight. Body weight was set to 350 kg for local cattle, 450 kg for crossbred cattle, and 400 kg for other livestock. It was assumed that 80% of the manure produced was collected, and all applied to fields for fertilization. Manure and fertilizer application rates were used to multiply with default emission factors extracted from the IPCC guidelines (IPCC, 2006). The available survey data was sufficient to follow Tier 2 guidelines for emissions from enteric fermentation (CH_4) for cattle, and Tier 1 for other livestock. Tier 2 takes into account the gross energy requirements of cattle with an annual milk production of 340 l yr^{-1} for local cattle breeds and 680 l yr^{-1} for crossbred cattle. This resulted in calculated emission factors of 20 kg CH_4 $head^{-1}$ yr^{-1} for local cattle, and 26 kg CH_4 $head^{-1}$ yr^{-1} for crossbred cattle. Tier 1 default emission factors were used for other animals: 5 kg CH_4 $head^{-1}$ yr^{-1} for sheep and goats, 1 kg CH_4 $head^{-1}$ yr^{-1} for pigs, and no emissions for poultry. We did not compute methane emissions from rice, nor emission from burning residue, since both activities were not common among the survey respondents. Given the low levels of fertilizer and industrial feed use, off-farm GHG emissions were not taken into account. Further, we excluded changes in soil organic C (SOC) stocks from the GHG calculations, assuming a steady-state. Firstly, changes in soil C stocks are slow and only visible in the long-term. Even potentially soil conserving agricultural practices have minimal impacts on SOC stocks across many tropical soils in SSA, at least partly due to high decomposition rates (Powlson et al., 2016; Palm et al., 2014). Moreover, modeling of SOC changes is still challenging, especially with limited input data availability. SOC sequestration is a complex process, and any potential increase rates will slow down and cease over time reaching a new equilibrium state. Therefore, the role of SOC sequestration in GHG balances and global mitigation efforts is limited (Sommer and Bossio, 2014). The GHG calculation was applied to all 884 households individually. Results were reported in three different ways: a) GHG per individual household (calculating kg CO2e hh^{-1} yr^{-1}); b) median GHG (kg CO2e hh^{-1} yr^{-} 1) per site and/or per FA class; c) contributions (%) of different sources to total GHG. For a detailed description of the calculations see Supplementary material.

2.4. Agricultural intensification scenarios

The scenarios in this study were closely modeled after key national policy programs, and effect sizes informed by published literature and expert estimations. Table 2 summarizes the key parameters and assumptions for each scenario.

2.4.1. Girinka

In 2006, the Government of Rwanda initiated the Girinka program (One Cow per Poor Family) (MINAGRI, 2006). Under Girinka, in-calf crossbred heifers are distributed to vulnerable farmers who pass on the first female calf to a poor neighbor. The program seeks to address malnutrition by increasing rural milk consumption, which currently lies with 13 l $person^{-1}$ yr^{-1} far below FAO recommended rate of 220 l. Participating households are selected by the community and should own no livestock and < 0.75 ha land (MINAGRI, 2006). Local cows produce around 2 l day^{-1} during lactation, while crossbreed cows can potentially reach 6 l day^{-1} (Kamanzi and Mapiye, 2012). However in reality, the poorest Girinka farmers have difficulty feeding their cow, mainly relying on low quality feeds such as collected natural grasses, banana pseudostems, and crop residues. This limits the productivity of crossbred cows to 2–4 l cow^{-1} day^{-1} (Klapwijk et al., 2014b). The Girinka scenario added one crossbred cow to each farm household without cattle and with < 0.75 ha land. Milk production of the Girinka cows (as for all other crossbred cows) was set to 680 l cow^{-1} yr^{-1}, using the estimations of Klapwijk et al. (2014b) and Lukuyu et al. (2009), while taking into account gestation and dry periods (Table 1).

2.4.2. Improved livestock feeding

Creating a resilient feed resource base and systematic crop-livestock integration are seen as major building stones to reach Vision 2020 (MINAGRI, 2009a). In 2009, the strategic plan for livestock nutrition improvement called for adequate on-farm mix of forage legumes and grasses and concentrate feeds under zero grazing (MINAGRI, 2009a). Restricted grazing has been confined to areas in Nyagatare and Gishwati, and otherwise only zero grazing or fenced grazing are allowed. Despite these efforts, most of the livestock herd is currently still inadequately fed (Lukuyu et al., 2009; Mutimura et al., 2013). To make optimal use of the limited land resources, high productivity fodder species such as Napier grass (*Pennisetum purpureum*) and high quality species such as *Brachiaria cv. Mulato II* have been promoted. *Mulato II* has 12–14% crude protein content, and can be grown on soils with lower fertility and is drought tolerant (Mutimura and Everson, 2012; Mutimura et al., 2015). Other options include leguminous forage shrubs such as *Leucaena diversifolia*. Supplementation with 2.2 kg leaf meal was shown to increase daily milk yield from 6 to 8 kg milk cow^{-1} day^{-1} (Myambi and Mutimura, 2012). Although land availability for additional forage production is limited in Rwanda, different forage species can be targeted to specific cropping system niches (Umunezero et al., 2016). The improved livestock feeding scenario assumed that local and crossbred milk production increased by 50% (from 340 to 510 l yr^{-1}) and 81% (from 680 to 1230 l yr^{-1}). Implicit in this scenario is that farmers grew the additional fodder necessary without changing current land use and expenses, thus integrating as intercrop or rotation or on previously unused areas of their farm such as boundaries and contours.

Table 1
Key parameters and assumptions of the three study scenarios.

	A. Girinka	B. Improved livestock feeding	C. Soil and crop improvement
Parameters	+ 1 crossbred cow for households without cattle and < 0.75 ha of land at milk production of 680 l yr^{-1}.	Milk production increases by 50% for local cattle (from 340 to 510 l yr^{-1}) and 81% for crossbred cattle (from 680 to 1230 l yr^{-1}).	Increase of crop production for maize, wheat, rice, potato, beans and cassava due to additional 45 kg fertilizer ha^{-1} across all households, corresponding to 16 kg N ha^{-1}. The crop yield response depends on baseline fertilizer application: + 100% for households without previous fertilizer use; + 50% for households with 1–6700 RWF ha^{-1} yr^{-1} fertilizer expenses; + 25% if expenses exceed 6700 RWF ha^{-1} yr^{-1}.
Assumptions	The gift cow can be fed to the extent that it produces 680 l yr^{-1} at no additional costs or change in crop production. The additional milk produced is half sold, half consumed by the household.	The increase of feed does not affect the production of food crops, and does not imply additional expenses. The extra milk is half sold, half consumed by household.	Buying better seeds does not generate extra expenses, but fertilizer purchase results in additional expenses of 2.4 USD kg^{-1} N. The extra crop produced follows the same pattern of crop sold vs. crop consumed.

2.4.3. Soil and crop improvement

In 2007, the Government of Rwanda commenced the Crop Intensification Program (CIP), aiming to increase productivity of six priority annual crops (maize, wheat, rice, potato, beans and cassava) for improved food security and self-sufficiency (MINAGRI, 2011). A major activity under CIP is importation and distribution of subsidized farm inputs through public-private partnerships. In addition, the National Fertilizer Strategy aims to reach an average mineral fertilizer application of 45 kg ha^{-1} yr^{-1} in 2017/18, increasing from an average fertilizer application level of 4.2 kg ha^{-1} in 1969–1993 (MINAGRI, 2014). The soil and crop improvement scenario assumed that 45 kg ha^{-1} fertilizer application increases crop yields of CIP priority crops 1) by 100% for those farm households with no fertilizer expenditure in the baseline study; 2) by 50% for those households that spent 1–6700 RWF ha^{-1} yr^{-1} on fertilizer; and 3) by 25% for those households that spent > 6700 RWF ha^{-1} yr^{-1} on fertilizer. Since the most commonly used fertilizers for food crops in Rwanda are NPK (17-17-17), urea (46-0-0) and DAP (46-0-18), we assumed an average overall N fertilizer content of 35%, thus the 45 kg fertilizer ha^{-1} correspond to 16 kg N ha^{-1}. Additional fertilizer expenses for the household were calculated using the conversion of at 2.4 USD per kg N.

3. Results

3.1. Diversity of farm households

Median family size varied between 3.8 and 5.0 household members. Median cropping area ranged between 0.6 and 1.3 ha per household, with smallest areas in Rusizi (0.63 ha) and Bugesera (0.79 ha). Median livestock herd size was smallest in Kirehe (0.2 TLU) and largest in Ruhango (0.93 TLU). Households in Gatsibo and Rubavu did not have any annual expenses for purchase of agricultural inputs, while in Ruhango and Rusizi the median value varied between 380 and 1400 Rwandan Francs (RWF). In all sites, off-farm income was small, with only Rubavu having relatively higher median values (Table 2).

3.2. Baseline food availability

The FA indicator, calculated for all individual households, showed a positive relationship with self-assessed status of food security. Respondents of the same household survey were asked to classify their own food security status as i) often insufficient food quantity; ii) sometimes insufficient food quantity; iii) sufficient quantity but not the desired type; or iv) sufficient quantity and desired type (Fig. 3). Overall, 46% of all households had < 2500 kcal available MAE^{-1} day^{-1}. Rubavu (30%) and Ruhango (34%) had fewest households below the 2500 kcal line, while Rusizi (52%) and Bugesera (53%) had highest percentages. Ruhango (3600 kcal MAE^{-1} day^{-1}) and Rubavu (3400 kcal MAE^{-1} day^{-1}) had the highest median FA, and Bugesera, Kirehe and Rusizi had the lowest (all 3200 kcal MAE^{-1} day^{-1}). The main contribution to FA originated from consumed and sold food crops - 81.2% in the low FA class, 64.3% in the medium FA class, and 53.1% in the high FA class. The share of cash crops increased from 2.5% for the low FA class to 3.5% for the high FA class. While the contribution of poultry was higher in the low FA class (3.2%) than in the high FA class (0.7%), the contribution of cattle showed the reverse pattern (26.8% in high FA class, and 5.9% in low FA class). Off-farm income was more important in the high FA class (15.5%) than in the low FA class (5.2%). Off-farm income contributed more to FA in the high FA class in Rubavu (32.0%) and Kirehe (22.5%) than in other sites. Cash crops contributed more to FA in Rubavu (6.1–7.9%) than in other sites (Figs.

Table 2
Agro-ecological and socio-economic characteristics of the survey districts. Annual rainfall and altitude data was obtained from the closest weather station of the Rwanda Meteorology Agency. Population density for each district was extracted from the 2012 Population and Housing Census and the National Institute of Statistics of Rwanda. All other data calculated from the household survey, and given in median with inter-quartile ranges in brackets. MAE refers to Male Adult Equivalent.

	Bugesera	Nyagatare	Karongi	Kirehe	Rubavu	Ruhango	Rusizi
Population density (people/km^2)	280	242	334	287	1039	510	418
Annual rainfall (mm)	854	633	1089	913	1205	1070	1419
Altitude (m)	1450	1450	1470	1500	1554	1700	1591
Family size (MAE)	3.8 (2.2)	4.4 (2.1)	4.1 (2.8)	4.1 (2.2)	5 (2.9)	4.1 (2.1)	4.8 (3.4)
Crop land (ha)	0.79 (1.6)	1 (1.2)	1.1 (2.1)	1.1 (1.6)	1.2 (1.7)	1.3 (2.3)	0.63 (1.5)
Number of crops	5 (3)	4 (3)	5 (1)	5 (3)	4 (2)	6 (2)	5 (2)
Livestock herd size (TLU)	0.76 (1.2)	0.46 (1.5)	0.8 (1.4)	0.2 (0.8)	0.5 (0.67)	0.93 (1.8)	0.51 (0.95)
Crop input expenses (RWF)	0 (3900)	0 (0)	0 (5200)	0 (5200)	0 (0)	380 (11000)	1400 (7300)
Off farm income (RWF)	0 (15)	0 (67)	0 (85)	0 (39)	46 (280)	0 (58)	0 (27)

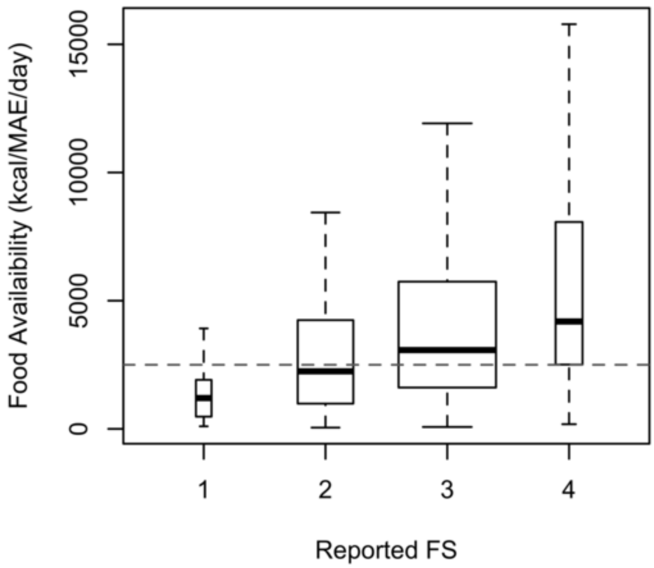

Fig. 3. FA in kcal MAE^{-1} day^{-1} compared to self-assessed food security from the same survey to explore confidence of the FA indicator. Respondents were asked to classify their own food security status as: i) often insufficient food quantity; ii) sometimes insufficient food quantity; iii) sufficient quantity but not the desired type; or iv) sufficient quantity and desired type. The red dashed line represents a FA level of 2500 kcal MAE^{-1} day^{-1}, the daily energy need of a male adult. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4a and 5a). FA was not correlated to land size (Fig. 1 Supplementary material).

3.3. Baseline GHG emissions

GHG emissions were correlated to livestock, with on average 1360 kg CO_2e per TLU (Fig. 2 Supplementary material). Across all sites, the largest contributor to GHG emissions was enteric fermentation (48.7% low FA, 48.9 medium FA, 47.6% high Fa), followed by emissions from manure (31.8%, 27.4%, 26.7%), and then direct and indirect emissions from soils (19.5%, 23.7%, 25.7%). 138 households (15.6% of the study population) did not emit any GHG emissions, and are represented by the blank space in Fig. 4b. These households did not own ruminants, and did not report applying fertilizer or manure to their fields. 53 households (6% of the population) had very low GHG emissions, remaining < 10 kg CO_2e hh^{-1} yr^{-1} (Fig. 4b). The highest median emissions were calculated for households in Ruhango (1506 kg CO_2e hh^{-1} yr^{-1}), followed by Bugesera (1116 kg CO_2e hh^{-1} yr^{-1}) and Karongi (1115 CO_2e hh^{-1} yr^{-1}). Lowest median emissions were derived for Kirehe and Rusizi with 395 and 663 kg CO_2e hh^{-1} yr^{-1} respectively. GHG emissions increased from low FA class to high FA class, with 50% of the total GHG being emitted by 22% of the households with the highest FA scores (Figs. 4b and 5b).

3.4. Scenario assessment and trade-offs

The effects of the three policy scenarios on FA and GHG emissions varied between sites and FA classes. Girinka only affected 26% of all households, but 49% within the low FA class. The scenario decreased households below the 2500 kcal MAE^{-1} yr^{-1} line from 46% to 35%, leading to a median net increase of 1843 kcal MAE^{-1} yr^{-1}. At the same time, GHG emissions increased by 1174 kg CO_2e hh^{-1} yr^{-1}. Improved livestock feeding reached 42% of all households, though only 10% in the low FA class and 66% in the high FA class. The scenario decreased the overall proportion of households below 2500 kcal MAE^{-1} yr^{-1} from 46% to 43%, leading to a median net increase of 755 kcal MAE^{-1} yr^{-1}. GHG emissions increased by 50 kg CO_2e hh^{-1} yr^{-1}. Soil and crop improvement affected 94% of all households with equally high shares (91–96%) in all FA classes. The scenario reduced the percentage of population below the 2500 kcal line from 46% to 40%, leading to a median net increase of 322 kcal MAE^{-1} yr^{-1}. GHG emissions increased by 23 kg CO_2e hh^{-1} yr^{-1}. (Fig. 6). Fig. 7 underlines trade-offs between FA and GHG emissions which varied across scenarios. Households that were not affected by a scenario are displayed as dots, while changes from baselines to scenario outcomes are denoted as arrows. While Girinka did not affect the majority of the households, it sharply increased both FA and GHG emissions for the impacted households, which originally had low GHG emissions (long and steep arrows). Improved livestock feeding did not affect many of the low FA households, but it increased FA for those impacted accompanied by only a minimal increase in GHG emissions (short and flat arrows). Soil and crop improvement affected almost all households (hardly any dots) with highly variable responses in FA and GHG (short and long arrows, and steep and flat arrows) (Fig. 7).

4. Discussion

4.1. Data limitations

Farmer-reported data, as used for this analysis, has its inherent limitations. Carletto et al. (2013b) compared farmer-reported farm sizes with empirical measurements. They showed that farmers with small land holdings (< 5 acres) tended to overestimate their land size, while farmers with larger land holdings (> 5 acres) underestimated the same. However, the differences balanced out, resulting in an only 3% overall discrepancy. Similar effects could be expected for farmer-reported crop and livestock yields that we used in this study. Although errors in farmer-reported data are high, it is the best method available to date to analyze large household populations.

4.2. Determinants of food availability

Following the correlation between calculated FA and self-assessed food security from the same survey (Fig. 3), we conclude that the FA indicator gives reasonable insight into variations in overall food security status across individual farm households, despite the strong underlying assumptions and simplifications. This corroborates findings of Frelat et al. (2016) and Hammond et al. (2016) who showed that the FA indicator correlated well with self-scoring of food security, the USAID Hunger and Food Insecurity Status indicator and household level diet diversity. Although FA is a potential supply indicator only and not necessarily reflecting full food security status, Hammond et al. (2016) also illustrated how households with at least 4000 kcal MAE^{-1} day^{-1} can qualify to be effectively food secure. The FA indicator has been found useful for quantifying key determinants of food availability in systems where agricultural productivity is one of the key limiting factors (Frelat et al., 2016; Ritzema et al., 2016).

The small land sizes and low livestock ownership were reflected in low FA scores (Figs. 4a and 5a). 46% of the population remained below the 2500 kcal MAE^{-1} day^{-1} line, which is comparable to other sites in East and West Africa like Lushoto (Tanzania), Wote (Kenya), Lawra (Ghana) or Borana (Ethiopia) (Ritzema et al., 2016). However, 46% is higher than 37% obtained from analyzing > 13.000 house-

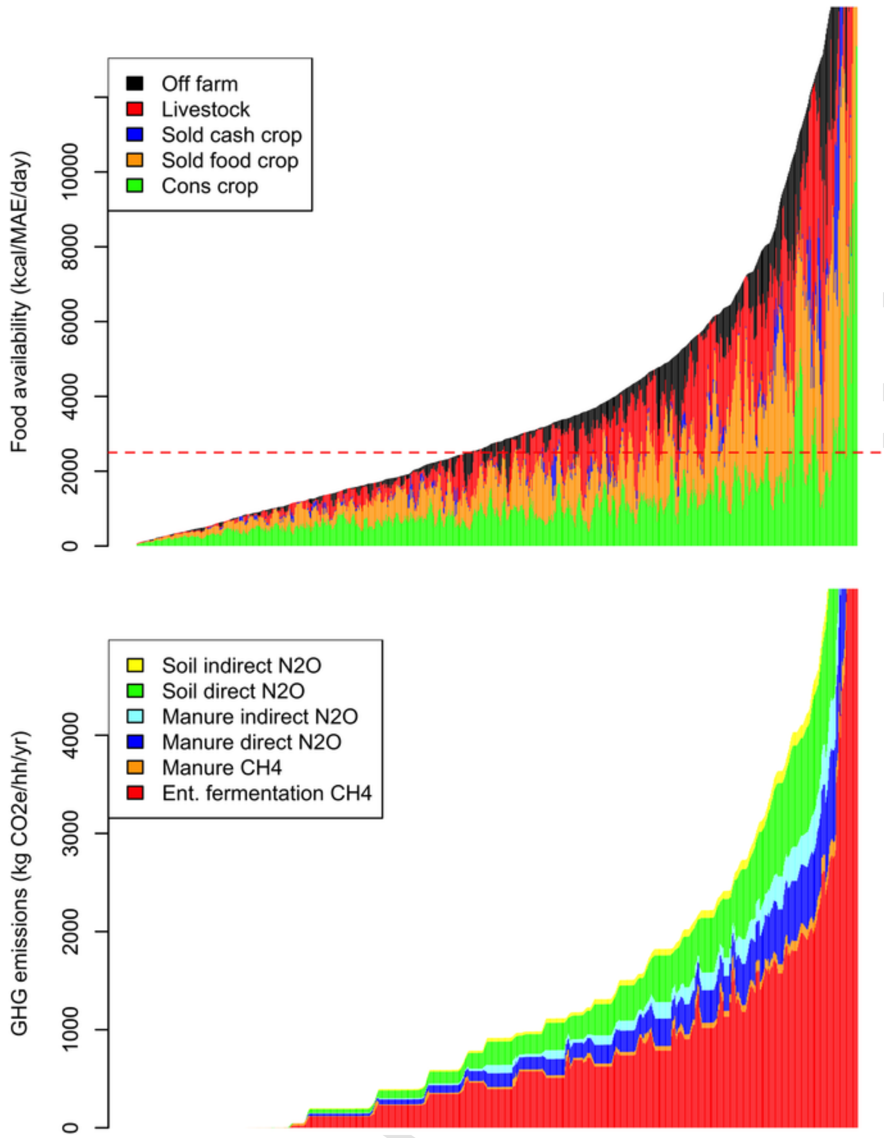

Fig. 4. (a) Overall distribution of FA across all study households in Rwanda. Each vertical bar represents one household, the colors represent its sources of energy, and the height represents total FA in kcal MAE^{-1} day^{-1}. The red dashed line depicts a food availability level of 2500 kcal MAE^{-1} day^{-1}, the daily energy need of a male adult; (b) Overall distribution of GHG emissions in kg CO2e hh^{-1} yr^{-1} across all sites in Rwanda. Each vertical bar represents one household, the colors represent the sources of GHG emissions, and the height represents the total amount of GHG in CO2e. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

holds across sub-Saharan Africa (Frelat et al., 2016). However, the dataset used for this study originates from 2006, and food availability has likely been changing since then. Between 2006 and 2011, the standard of living of Rwandans has considerably improved, with most drastic poverty reduction in the Northern Province (NISR, 2011). Rwanda's Vision 2020 aspires to reduce the poverty rate to 30% in 2020, and increase caloric consumption to 2200 kcal day^{-1} $person^{-1}$ (MINECOFIN, 2000).

The Southern (Rusizi) and Eastern (Bugesera, Kirehe, Gatsibo) parts of the country showed lower FA than the North (Rubavu) and South-West (Karongi, Ruhango) (Fig. 5a). Ruhango benefits from its proximity to Kigali as well as its central location, opening up economic opportunities such as trade. Karongi has access to income from fishing in Lake Kivu. Bugesera, Kirehe and Gatsibo suffer from low soil fertility, acidic soils and pronounced dry spells. These findings are largely in line with research from the National Institute for Statistics in Rwanda (NISR, 2011), which reported highest poverty levels in the Southern province and lowest close to Kigali. Despite the differences between the regions, we found consistent patterns in the factors determining FA: Food crops, consumed or sold, were the mainstay of food availability in Rwanda, regardless of FA class or site. Higher FA positively correlated with livestock owning, off-farm income, and cattle numbers, pointing to potential pathways out of poverty. Cash crops played a negligible role in Rwanda's FA, and possible reasons could include lack of land and investments in value chain development that would be needed to let them play a comparable role as in Western Kenya and North Eastern Tanzania (Ritzema et al., 2016). The NISR survey (2011) further confirmed the crucial role of off-farm job creation for poverty reduction, measuring highest poverty among those exclusively relying on agricultural income. It also showed that increases agricultural productivity and livestock ownership in especially the Northern, Eastern and Western provinces contributed considerably to poverty reduction. Little progress was made in the poor Southern Province (NISR, 2011).

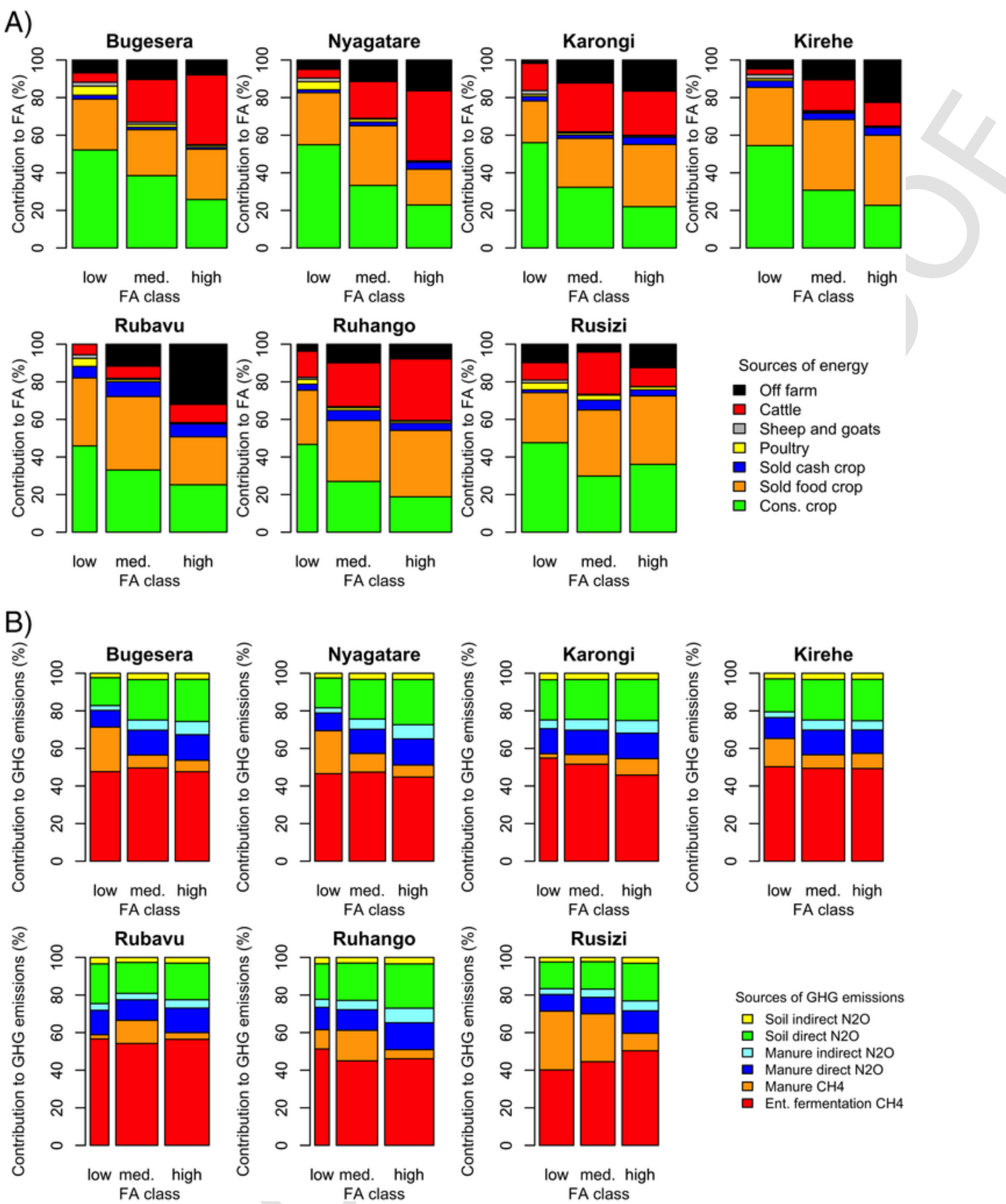

Fig. 5. (a) Relative contribution (%) of household activities to FA (kcal MAE^{-1} yr^{-1}) per district and FA class. FA classes are defined as follows: low FA class with < 1500 kcal MAE^{-1} yr^{-1}, medium FA class with 1500–4000 kcal MAE^{-1} yr^{-1}, high FA class with > 4000 kcal MAE^{-1} yr^{-1}; (b) Relative contribution (%) of GHG emission sources to overall GHG per district and FA class. FA classes are defined as follows: low FA class with < 1500 kcal MAE^{-1} yr^{-1}, medium FA class with 1500–4000 kcal MAE^{-1} yr^{-1}, high FA class with > 4000 kcal MAE^{-1} yr^{-1}. Households with no GHG emissions were omitted from this graph.

4.3. GHG emission determinants

Farm level GHG emissions in Rwanda were highly correlated with livestock ownership (Fig. 2 Supplementary material). Households in sites with the highest cattle numbers therefore showed highest CO_2e emissions (Fig. 5a). Valentini et al. (2014) assign 61% of total emissions from SSA to agriculture, forestry and other land use, with CH_4 emissions from ruminant enteric fermentation being responsible for a large share of agricultural emissions. A study from Western Kenya confirmed the high contribution of livestock to the overall GHG balance of such smallholder systems (Seebauer, 2014). Also, a rapid assessment for Rwanda found that enteric fermentation was one of the largest contributors to GHG emissions at national level (Dfid et al., 2009).

However, GHG assessment results need to be interpreted with caution. Firstly, comparability between different assessments is low. Colomb et al. (2013) investigated 18 landscape-scale GHG calculators and although all of them were based on the IPCC guidelines, they differed in scope, calculation method and reporting units

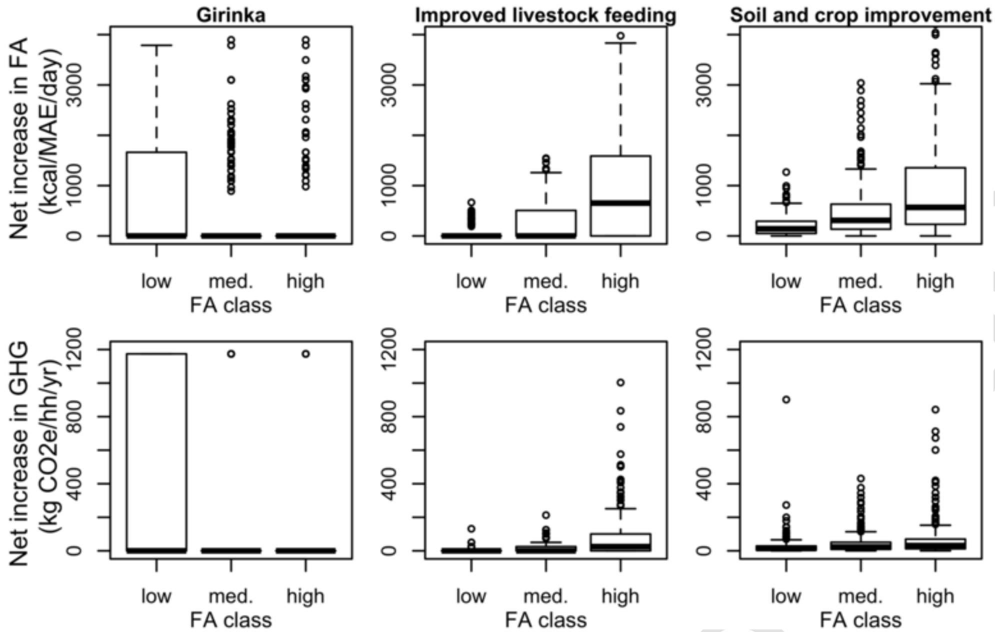

Fig. 6. Net median changes of FA (kcal MAE^{-1} day^{-1}) and GHG emissions (kg CO2e hh^{-1} yr^{-1}) per FA class across all districts for the different policy scenarios Girinka, improved livestock feeding, and soil and crop improvement. FA classes are defined as follows: low FA class with < 1500 kcal MAE^{-1} yr^{-1}, medium FA class with 1500–4000 kcal MAE^{-1} yr^{-1}, high FA class with > 4000 kcal MAE^{-1} yr^{-1}.

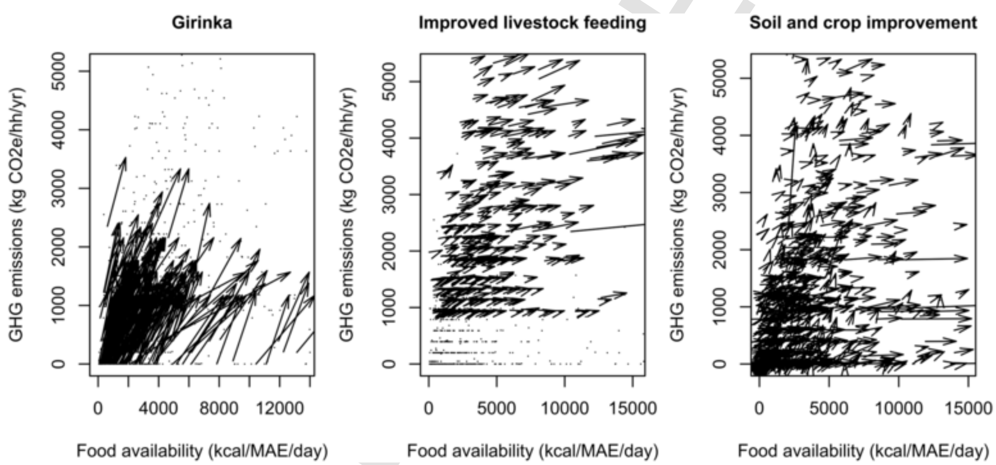

Fig. 7. Relationship between FA (kcal MAE^{-1} day^{-1}) and GHG emissions (kg CO2e hh^{-1} yr^{-1}) for the baseline (beginning of the arrow) and the different policy scenarios Girinka, improved livestock feeding, and soil and crop improvement (end point of the arrows).

(Colomb et al., 2013). Secondly, IPCC Tier 1 were developed for national scale inventories, but came into use at farm scale when more data was unavailable. Tier 1 emission factors are mostly derived from OECD country data as empirical measurements from SSA are rare. Due to differences in breeds, climates, feeding and management systems, it became generally acknowledged that IPCC Tier 1 and 2 methods overestimate livestock related emissions (enteric fermentation, manure) from SSA (Herrero et al., 2013a). Recent empirical measurements of CH_4 and N_2O emissions from livestock excreta in Kenya confirmed that IPCC Tier 1 methods overestimate fecal CH_4 and urine N_2O by a factor two, and fecal N_2O even 10 – 20-fold (Pelster et al., 2016). Therefore, close relation between TLU and total GHG emissions from agricultural activity in Rwanda therefore could be, at least partly, a consequence of methodological shortcomings. Until more studies are available to re-define emission factors across different tropical climates and for all GHG emission sources over longer periods, the IPCC guidelines are the best available method to estimate whole farm GHG budgets.

4.4. Scenario assessment

Although policy impacts are dynamic and can differ in short and long term, the modeling approach we used is a static, short term exploration of potential impacts of policy scenarios that have no financial or logistical constraints to reach its target group. Our analysis illustrates how intensification scenarios result in different potential impacts and trade-offs between food availability and GHG emissions across the population.

Girinka reached the smallest number of overall households (26%), but it specifically impacted the low FA class. Therefore, it achieved the most drastic decrease in households below 2500 kcal MAE^{-1} yr^{-1} (11%). However, this came at the largest cost in GHG increase due to the increase in animal numbers. While Girinka strongly acted pro-poor, it could hardly be considered climate smart due to the steep increase in GHG emissions. In addition, adding cows to the poorest households would have strong implications for feed availability and labour demands (Klapwijk et al., 2014b).

Improved livestock feeding impacted more households overall (42%), but mainly within the medium and high FA classes where cattle ownership is more concentrated. Consequently, the decrease of households below 2500 kcal MAE^{-1} yr^{-1} was only 3%, making it is the least equitable scenario. The increase in GHG emissions is relatively small, thereby decreasing emission intensity per produced energy. This is in line with another study that showed how improved livestock feeding strategies in Tanzania can decrease CH_4 emission intensities while increasing income and food security (Shikuku et al., 2016). Improved livestock feeding is currently considered one of the most promising climate-smart practices. With an accelerated adoption rate, it could considerably contribute towards reaching a triple win between food security, adaptation, and mitigation (Lipper et al., 2014; Campbell et al., 2014).

Soil and crop improvement is the most equitable strategy, affecting almost all households (94%) equally distributed across all FA classes. Although it decreased households below 2500 kcal MAE^{-1} yr^{-1} by 6%, the net median increase in energy availability was lowest of all scenarios (322 kcal MAE^{-1} yr^{-1}). The scenario also resulted in the smallest increase in GHG emissions.

These results were obtained by using relatively simple calculation schemes for both food availability and GHG emissions, two of the three pillars of CSA. More detailed model analyses could give more accurate numbers, but this study gives a first insight in the main patterns and major effects of the different intensification scenarios. The approach is also easily applicable across large numbers of farm households and uses relatively easily available information, thereby allowing rapid impact assessment across contrasting systems. This type of analysis is needed for comparative assessment and prioritization of policy options, and scale up possible farm household level responses to regional or country levels (e.g. van Wijk, 2014).

5. Conclusions

Across all sites, 46% of households were below the 2500 kcal MAE^{-1} yr^{-1} line, with lower food availability in the Southern and Eastern Rwanda. Consumed and sold food crops were the mainstay of food availability, contributing between 81.2% (low FA class) to 53.1% (high FA class). Livestock and off-farm income were the most important pathways to higher FA. Baseline GHG emissions were low, ranging between 395 and 1506 kg CO_2e hh^{-1} yr^{-1} per site, and livestock related emissions from enteric fermentation (47.6–48.9%) and manure (26.7–31.8%) were the largest contributors to total GHG emissions across sites and FA classes. GHG emissions increased with FA, with 50% of the total GHG being emitted by 22% of the households with the highest FA scores. Scenario assessment of the three policy options showed strong differences in potential impacts: Girinka only reached one third of the household population, but acted highly pro-poor by decreasing the households below the 2500 kcal MAE^{-1} yr^{-1} line from 46% to 35%. However, Girinka also increased GHG by 1174 kg CO_2e hh^{-1} yr^{-1}, and can therefore not be considered climate-smart. Improved livestock feeding was the least equitable strategy, decreasing food insufficient households by only 3%. However, it increased median FA by 755 kcal MAE^{-1} yr^{-1} at a small GHG increase (50 kg CO_2e hh^{-1} yr^{-1}). Therefore, it is a promising option to reach the CSA triple win. Crop and soil improvement resulted in the smallest increase in median FA (FA by 755 kcal MAE^{-1} yr^{-1}), and decreasing the proportion of households below 2500 kcal MAE^{-1} yr^{-1} by 6%. This came only at minimal increase in GHG emissions (23 kg CO_2e hh^{-1} yr^{-1}). All policy programs had different potential impacts and trade-offs on different sections of the farm household population. Quick calculations like the ones presented in this study can assist in policy dialogue and stakeholder engagement to better select and prioritize policies and development programs, despite the complexity of its impacts and trade-offs.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2017.02.007.

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