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Carbon footprint of smallholder farms in Central Madagascar: The integration of agroecological practices

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A B S T R A C T

The carbon footprint (CFP) assessment of smallholders offers key information on the capacities and challenges for greenhouse gas (GHG) mitigation at farm scale. This allows prioritizing the practices that ensure both the food security of farmers and the low carbon impact associated to climate change. To tackle food security challenges and to maintain sustainable environment production, agroecological practices were planned for farmers in the Itasy region, Central Highlands of Madagascar. The project consisted of agroforestry and forestry systems, composting of organic matters, and system of rice intensification. The goals of this study were (i) to assess the CFP of farms in the Itasy region Central Madagascar, (ii) to assess the impact of agroecological practices adopted by farmers on farms CFP, and (iii) to compare the impact of Tier 1 and Tier 3 factors for carbon removal in woody biomass and in cropland soils on farms CFP. For these purposes, a survey of 192 representative farms was realized during the years 2012–2013. Agroecological practices integrated at farm scale reduced significantly farms CFP up to 364% in terms of land surface and up to 578% in terms of food production, suggesting an important GHG sequestration at farm scale. Main sources of GHG at farms scale were: nitrous oxide from soil management (25%), methane from rice cultivation (24%), livestock manure management (24%), and enteric fermentation (23%). Trees planted in agroforestry and forestry systems offered the highest GHG mitigation benefits. Tier 1 factors overestimated up to 7 times higher the farms CFP compared to Tier 3 factors. This study highlights that the integration of agro-ecological practices at farm scale offers significant GHG mitigation and carbon sequestration in Malagasy context, thus giving an alternative for climate change mitigation.

1. Introduction

Agricultural lands occupy 37% of the earth's land surface. An important amount of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) is however released by related activities including food production, livestock, fertilizers, pesticides, soil management, machinery and transport (IPCC, 2006). Moreover, modern agriculture increase and irrigation systems pollute more the environment (Mahdizadeh Khasraghi et al., 2015; Valipour, 2012a, 2012b; Valipour et al., 2015; Yannopoulos et al., 2015). The agricultural sector accounts up to 52% and 84% of the global anthropogenic CH4, and N2O emissions (Smith et al., 2008); yet, it is also recognized as a considerable sink of GHG by sequestering carbon in soils and in woody biomass (Hillier et al., 2009; Lal, 2004a,b; IPCC, 2006). During the last decade, emissions of GHG from crops and livestock production have significantly increased in developing countries, due to an increase of the total agricultural outputs (Tubiello et al., 2014).

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The huge interest in GHG emissions and their impact on the Global climate have inspired the carbon footprint (CFP) assessment; which is defined as the total sets of GHG emissions caused by an organization, event, product or person (IPCC, 2006). Thus, the CFP is the quantity of GHG expressed in units of CO_2 equivalent (Wiedmann and Minx, 2008) and remains as a strong indicator of GHG intensity of activity or organization (Pandey and Agrawal, 2014) while the life cycle analysis (LCA) method aims to estimate the environmental impact of the production, the use and the disposal of a product (Payraudeau and van der Werf, 2005). Household, companies, cities, region and country make use of CFP assessment (Peters, 2010) as well as livestock and animal production areas (Luo et al., 2015; Rotz et al., 2010; Ruviaro et al., 2015; Topp and Rees, 2008), energy consumption sectors (Kenny and Gray, 2009), food production (Coley et al., 2009; Jianyi et al., 2015; Kristensen et al., 2015; Pathak et al., 2010; Yan et al., 2015), and agricultural practices (Hillier et al., 2009; Knudsen et al., 2014; Yuttitham et al., 2011).

In Madagascar, the economy stands on agriculture and 80% of the population live from agriculture and livestock products in rural areas (INSTAT, 2011). Best part of farmers still practice traditional agriculture and are accordingly strongly liable to natural resources and climate variability. Hence any climatic disturbance possibly will threaten food security and livelihood of Malagasy farmers (INSTAT, 2011): in fact, when they produce less, their income goes down whereas their costs go up (Lobell et al., 2011) and this problem occurs in other developing countries (Brown and Funk, 2008; Parry, 2007).

Agroecological practices (AP) seek sustainable farming systems that optimize and stabilize yields (Silici, 2014). In the Itasy region, the agroecology concept was primarily proposed to farmers to cope with the food security by improving crop productivity, diversifying agricultural products, and by preserving the natural resources like soils and water.

In order to improve the incomes and the benefits of farmers, trees within agroforestry and forestry systems were planted and composting of organic matters was promoted in the region. Thus, a wider range of products were sold in local markets (woods and fruits) and crop production was improved with fertilized soil.

The System of rice intensification (SRI) is mainly characterized by the young seedlings transplantations and the alternation of drought and wet period of rice field (Stoop et al., 2002). The SRI increases the productivity of irrigated rice by changing the management of plants, soil, water and nutrients (http://sri.cals.cornell.edu/) and was first used in Madagascar in the 1980s. In the Itasy region, SRI particularly increases the rice yield from 2 t/ha to 5 t/ha.

In Madagascar, former works carried out on the environmental impact of AP adoption; including GHG fluxes and carbon sequestration were mainly done at plot scale (Chapuis-Lardy et al., 2009; Fanjaniaina, 2012; Razafimbelo, 2005). Therefore, this paper aimed to study the contribution of these AP to climate change and their potential of mitigation at farm scale.

Furthermore, the Tier 3 method using country specific factors (IPCC, 2006) was used in this study to estimate carbon removal in woody biomass and in cropland soils instead of the Tier 1 method which uses the default factors provided by the IPCC (2006).

Therefore, the objectives of this article were: firstly, to assess the CFP of farms in the Itasy region; and secondly, to assess the impact of different levels of AP adoption on farms CFP; and thirdly, to compare the impact of Tier 1 and Tier 3 factors for carbon removal in woody biomass and in cropland soils on farms CFP. This will enable the future analysis of the potential climate mitigation of smallholders and the promotion of the best mitigating practices.

2. Materials and methods

2.1. Description of case study

The study was conducted in the Itasy region, Central Highlands of Madagascar (46°54′22.66″E, 18°57′25.85″S). The region is 900–1500 m above sea level and has a tropical climate of altitude.

Agriculture and livestock provide income for farmers and production is mainly set for family consumption.

Lands are 20% irrigated, and the 80% are used for rain fed rice, agroforestry, forestry and for annual crops such as cassava, maize and bean. Agroforestry is the association of annual crops and trees which were mainly fruit species sold on local market. Forestry is chiefly dominated by *Eucalyptus* sp. and *Pinus. sp* that are utilized for household energy and for timber.

Cattles are exploited for animal traction and as source of manure.

As chemical fertilizers (urea, NPK) and pesticides are expensive for farmers, they are only applied on cash crops like vegetables and fruits like oranges.

In this case study, 192 farms were selected in order to represent the studied region in terms of size, means of production, crop system diversification, and education level of the household head.

The 192 farms were classified in four clusters according to their level of AP adoption. Cluster 1 ($n = 120$) and cluster 2 ($n = 44$) grouped farms with very low and low AP adoption levels whereas cluster 3 ($n = 10$) and cluster 4 ($n = 18$) grouped the farms with medium and high AP adoption level (Table 4). Planting trees was the most adopted practice followed by composting organic matter and SRI. Cluster 4 had the most important number of trees in agroforestry and forestry systems (>1000 trees). Cluster 3 ($n = 10$) differed from all clusters by the importance of compost produced annually on the farms (>10 t yr^{-1}). Cluster 1 ($n = 120$) and cluster 2 ($n = 44$) were characterized by small piece of land (1–1.5 ha) and a few number of cattle (an average of 2 heads per farm). Cluster 3 and cluster 4 gathered the relatively wealthy farms with an average cropland surface estimated around 3.2 ha.

2.2. Farm survey and resource flow mapping

Surveys of 192 farms were conducted during the years 2013–2014 through interviews of household heads, and were completed by fieldwork observations and measurements. A questionnaire was elaborated in order to collect complete information dealing with the structure of and activities within each farm.

Data collected included (i) Farm description such as location, land surface and production; (ii) Agriculture activities such as main crops, adoption of irrigated rice system, use of manure, pesticides and chemical fertilizers, burning of biomass, and organic matter added to soils; (iii) Livestock, including the type and number of animal heads; (iv) Forestry and agroforestry data such as number, age and species of trees; (v) Energy consumption, in particular fossil and renewable energy.

To assess the degree of AP adoption by farmers, data regarding trees planting, composting of organic matters and adoption of SRI were particularly evaluated for each farm.

Each farm was considered as a whole system with different compartments: household's habitation, annual crop fields, paddy rice fields, agroforestry and forestry fields, and livestock. Each compartment was characterized considering surface (ha), cropping techniques, main productions and inputs. Resource flows between compartments were assessed; for instance, the quantity of manure from livestock to crop field. Then, the resource flow map of each farm was drawn using the approach suggested by Tittonell et al. (2006). This map shows the flows of inputs and outputs to and

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from the different compartments of a farm. It also provides an overview of the structure and the functioning of each farm. Then, the system boundary was defined by the perimeter of each farm and integrated the inputs and outputs (Fig. 1a).

2.3. Carbon footprint calculation

To assess farm CFP, especially GHG mitigation and GHG removal strategies, we adopted a whole farm system modeling approach (Schils et al., 2007) so that we could take into account all changes in GHG emission and in carbon removal arising from alternative mitigation practices adopted in another sector of the farming system.

Many GHG emission protocols and standards are available at international level, such as, the GHG protocol of World Resource Institute (WRI), the ISO 14064, the Product Life Cycle Standard and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Pandey et al., 2011; Rugani et al., 2013). The 2006 IPCC Guidelines for National Greenhouse Gas Inventories, was relevant for this study for its detailed methodological approach on GHG emissions and removals quantification in the agricultural sector.

The volume 4 of the IPCC particularly provides guidance for GHG inventories in Agriculture, Forestry and Other Land Use (AFOLU) sector.

Inventories of GHG emissions and carbon removal in each compartment were carried out to estimate the total annual flux of GHG associated to each of the farm compartments previously identified (Fig. 1b). The three main GHG of the AFOLU sector including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were considered in the inventories; then expressed in terms

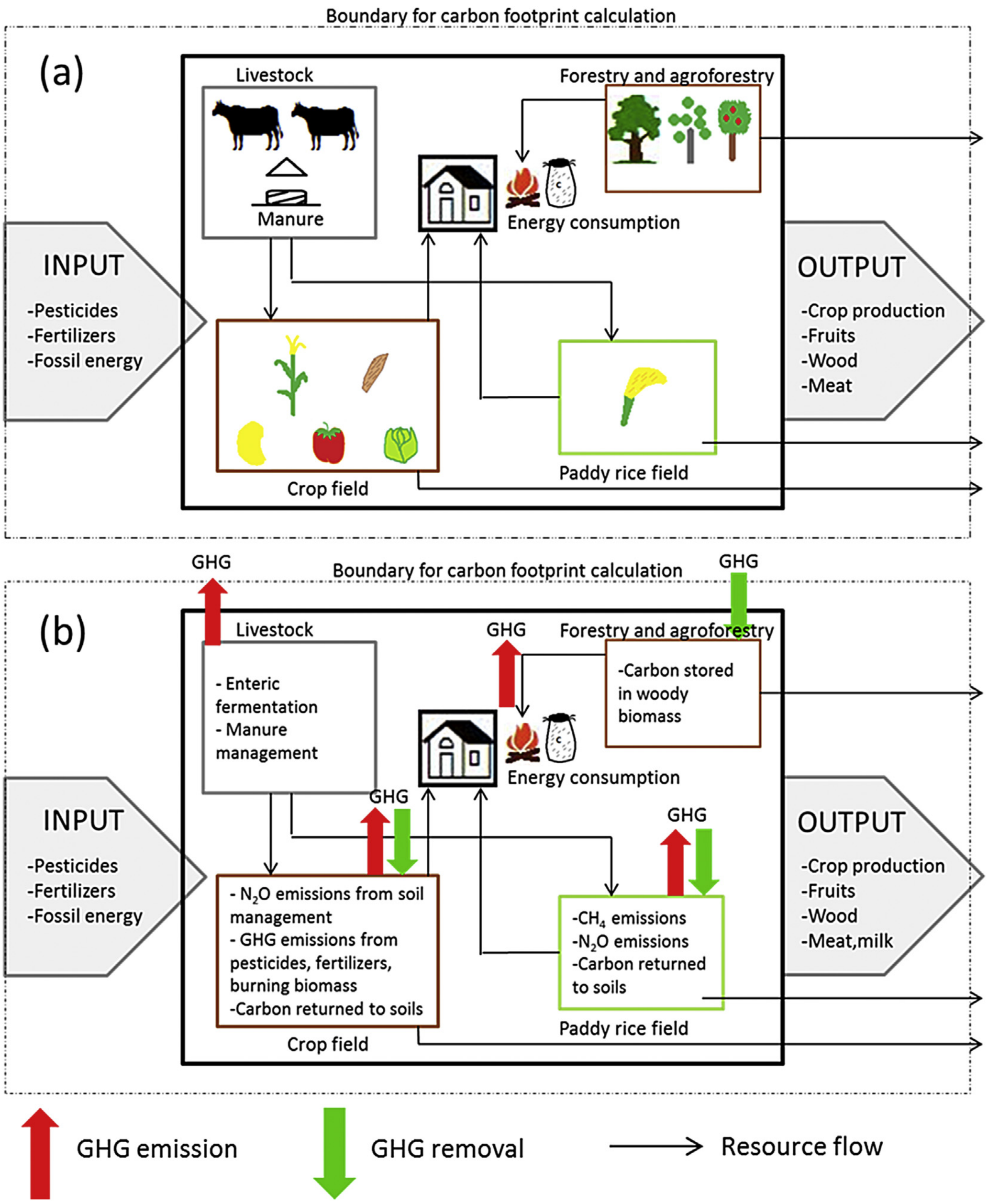

Fig. 1. Farming system compartments and GHG inventory.

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of CO_2 equivalent by using the Global Warming Potentials provided by IPCC (2006) ($CH_4 = 25$; $N_2O = 298$; $CO_2 = 1$).

CFP of each farm was calculated using the equation bellow:

$$\text{Carbon Footprint } (tCO_2 \text{ eq.}) = \sum \text{GHG Emissions } (tCO_2 \text{ eq.}) - \sum \text{GHG Removal } (tCO_2 \text{ eq.}) \quad (1)$$

GHG emissions were accounted as positive value whereas GHG removal as negative (Pandey and Agrawal, 2014), so CFP value could has a positive or negative value.

The farm CFP was expressed in terms of cropland area in $tCO_2eq.ha^{-1}\cdot yr^{-1}$ and in terms of crop production in $tCO_2eq.t^{-1}\cdot yr^{-1}$.

Furthermore, the 2006 IPCC guidelines propose methods at three levels of detail, from Tier 1 (the default method) to Tier 3 (the most detailed method) to estimate GHG emissions and removals from agricultural sector. The Tier 1 methods are designed to be the simplest to use, for which equations and default parameter values (e.g., emission and stock change factors) are provided by the IPCC (2006). The most detailed Tier 3 method used data adapted to a specific country and obtained from models and inventory measurements tailored to address national circumstances. These higher order methods provide estimates of greater certainty than lower tiers. In this case study, Tier 3 factors for carbon removal in woody biomass and cropland soils were available at national and regional scale, therefore we carried out a comparison between farms CFP by using these Tier 1 and Tier 3 factors.

2.3.1. Estimation of GHG emissions at farm scale

Greenhouse gas emissions from farm activities were calculated using Equation (2) (IPCC, 2006).

$$\text{GHG Emission} = \text{Data on activity} \times \text{Emission factor} \quad (2)$$

Data on activities were collected from farm survey (for example land surface, quantity of fertilizers …) and emission factors were selected from IPCC (2006) and from other literatures adapted to Malagasy conditions.

According to the IPCC (2006) guidelines for GHG inventories, 11 GHG sources were identified: CH_4 emission from rice cultivation, direct and indirect N_2O emission from managed soils, CO_2 emission from liming and urea fertilization, GHG emission from pesticide, biomass burning, livestock enteric fermentation, livestock manure management, renewable and fossil energy consumption (Table 1).

2.3.2. Estimation of carbon removals at farm scale

In the agriculture sector, adding organic matter such as compost into the soils and the tree planting are the main practices contributing to carbon removals.

Soil carbon sequestration was one of the processes recognized by the IPCC to remove CO_2 from the atmosphere (IPCC, 2006). It can be improved by some agricultural management practices which were already considered as significant climate change mitigation options (Hutchinson et al., 2007). The use of compost, organic manure, and crop residues were identified as one of the strategies to increase soil carbon sequestration (R. Lal, 2004a,b).

The mineralization rate of each type of organic matter applied by farmers (crop residues biomass, cattle manure and compost) was available from previous studies conducted in Madagascar allowing the calculation of the Tier 3 factors corresponding to the annual amount of carbon returned in the cropland soils (Falinirina, 2010; Rabetokotany, 2013; Razafimbelo, 2005).

The mineralized carbon from the total carbon found in the dry matter was subtracted to get the carbon returned in cropland soils (Table 2). These Tier 3 factors were used for farms CFP calculation in this study.

In this study, both Tier 1 and Tier 3 factors were used to respectively calculate the carbon removal in cropland soils and the farm CFP.

The estimation of Tier 1 factors for carbon removal in cropland soils followed the IPCC guidelines in order to make the difference between the use of Tier 1 and Tier 3 factors.

Therefore, the Tier 1 factor was calculated using Equation (3), from IPCC (2006) guidelines.

$$\Delta C = (SOC_0 - SOC_{(0-T)})/D \quad (3)$$

Where ΔC = annual change in carbon stocks in mineral soils ($tC.yr^{-1}$),

SOC_0 = soil organic carbon stock in the last year of an inventory time period (tC)

$SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period (tC)

Table 1
GHG emissions from farm activities.

Farm activities	GHG	Parameters considered	Emission factor references
Irrigated rice cultivation	CH_4	Type of ecosystem Water regime Type and amount of organic amendments Cultivation period of rice Annual harvested area of rice	IPCC, 2006
Adding nitrogen (N) source in managed soils	N_2O	Direct and indirect emissions Synthetic N fertilizers Organic N applied as fertilizer N in crop residues (above and below ground)	IPCC, 2006
Adding lime	CO_2	Annual quantity of calcic limestone or dolomite	IPCC, 2006
Use of urea fertilization	CO_2	Annual quantity of urea fertilization	IPCC, 2006
Use of pesticide	CO_2	Annual quantity of insecticides, fungicides and herbicides	Lal, 2004a,b
Biomass burning	CH_4, N_2O	Pasture and agricultural residues Area burnt Mass of biomass available for combustion	IPCC, 2006
Livestock enteric emission	CH_4	Number of livestock head species	IPCC, 2006
Manure management	CO_2 CH_4, N_2O,	Stockpiling manure and composting Annual quantity of manure	Pattey et al., 2005
Energy consumption	CO_2 CH_4, N_2O,	Renewable energy (firewood and charcoal) Fossil energy	(R Lal, 2004a,b) IPCC, 2006

Table 2
Tier 3 factors of carbon returned in soils according to the type of organic matter.

Organic matter	Carbon returned in soils (% of carbon in organic matter)	Reference
Crop residues	11	Razafimbelo, 2005
Cattle manure	57	Rabetokotany, 2013
Pig manure	83	Rabetokotany, 2013
Poultry manure	36	Rabetokotany, 2013
Compost	85	Falinirina, 2010

D = Time dependence of stock change factors (20 years)

SOC_0 and $SOC_{(0\text{-}T)}$ were calculated using Equation (4), where the reference carbon stocks and stock change factors are assigned according to the land-use and management activities and corresponding areas at each point of the inventory time.

$$SOC = \sum (SOC_{REF} \times F_{LU} \times F_{MG} \times F_I \times A) \quad (4)$$

SOC_{REF} = the reference carbon stock, t C ha^{-1} (47 tC ha^{-1} for Malagasy conditions)
F_{LU} = stock change factor for land-use systems
F_{MG} = stock change factor for management regime
F_I = stock change factor for input of organic matter

All these stock change factors were provided by the IPCC (2006).

Planting trees offers environmental benefits such as carbon sequestration in woody biomass (Jose, 2009). Tier 3 factors for carbon removal in woody biomass were obtained from previous studies conducted as part of the project “Agroecology and forestry farming in the Itasy region” (http://www.etcterra.org/en/projects/mahavotra).

Biomass measurement was performed from dendrometric inventories: measure of the Diameter at Breast Height (DBH), 1.30 m above the ground, and the height of the tree. Allometric equations adapted to climatic characteristics of the region were used to estimate the weight of trees from these measurable parameters in the field. Biomass was measured for the 12 tree species most planted by farmers: *Eucalyptus camaldulensis, Eucalyptus robusta, Eucalyptus citriodora*, *Pinus kesiya, Acacia mangium, Acacia auriculiformis, Melia azadiracht, Coffea arabica, Litchi chinensis, Mangifera indica, Persea Americana, and Citrus* sp.

In order to integrate the evolution of the tree growth, three age groups were defined in the sampling design: plantations less than 5 years old, between 5 and 10 years old and more than 10 years old. Because the biomass growth patterns showed relationship with plantation age and wood density, carbon removal annually in woody biomass was calculated for each species considering its age and wood density (Table 3). The equation of Brown (1997) was used to estimate carbon sequestration in woody biomass, as seen in Equation (5):

$$Carbon = Biomass \times 0.5 \quad (5)$$

Additionally, farms CFP using Tier 3 and Tier 1 factors for carbon removal in woody biomass were compared in this study.

For Tier 1 factors, in order to obtain the carbon annual sequestration in woody biomass, the generic allometric equation of Chave et al. (2005) for biomass measurement in moist forests measurement was used, as provided in Equation (6):

$$\text{Biomass (kg)} = d \times \exp\left(-0.667 + 1.784\ln(D) + 0.207(\ln(D))^2 - 0.0281(\ln(D))^3\right) \quad (6)$$

where d = wood density ($g \cdot cm^{-3}$) and D = diameter of trees at 1.30 m from soil surface (cm)

Finally, biomass was converted into carbon using the equation of Brown (Equation (5)) and divided by tree age.

2.4. Development of a dedicated farm carbon footprint calculator

Although many CFP calculators are available online, these tools are usually designed for a specific activity or for a given country. Moreover, the emission and removal factors are typically already incorporated in these tools (Padgett et al., 2008) which are not necessarily adapted to the current study conditions. The TropiC Farm Tool, developed in Microsoft Excel, is an appropriate calculator for the Malagasy conditions, as it integrated all suitable GHG emission and GHG removal factors.

TropiC Farm Tool was elaborated to facilitate and to standardize the calculation of all farms CFP. TropiC Farm Tool facilitates and standardizes the calculation of all farms CFP. This tool was suitable for farm level application as well as for large scale studies by aggregating activity data.

It was made of 6 Excel sheets corresponding to “farm description”, “agriculture”, “livestock”, “forestry”, “energy consumption” and “results” (Fig. 2) in a way that users can visualize directly GHG emission and removal for each section of the farm and for the whole farming system (TropiC Farm Tool, 2013).

Once, GHG emission and removal factors were integrated in the calculator, only the data from each farm activities remained to be entered for the CFP calculation following Equation (1).

2.5. Data analysis

Statistical analyses were performed both on data from farm

Table 3
Tier 3 factors of annual carbon sequestration in woody biomass.

Wood density	AGB (kgC $tree^{-1}$ yr^{-1})			BGB (kgC $tree^{-1}$ yr^{-1})			AGB + BGB (kgC $tree^{-1}$ yr^{-1})		
	<5 yr	5-10 yr	>10 yr	<5yr	5-10 yr	>10 yr	<5yr	5-10 yr	>10 yr
Inferior to 0.5	1.41	15.7	16.49	0.28	3.14	3.3	1.69	18.84	19.79
Between 0.5 and 0.7	1.24	7.93	22.26	0.25	1.59	4.45	1.49	9.52	26.71
Superior to 0.7	0.24	4.9	10.66	0.05	0.98	2.13	0.29	5.88	12.79

AGB: above ground biomass, BGB: below ground biomass.

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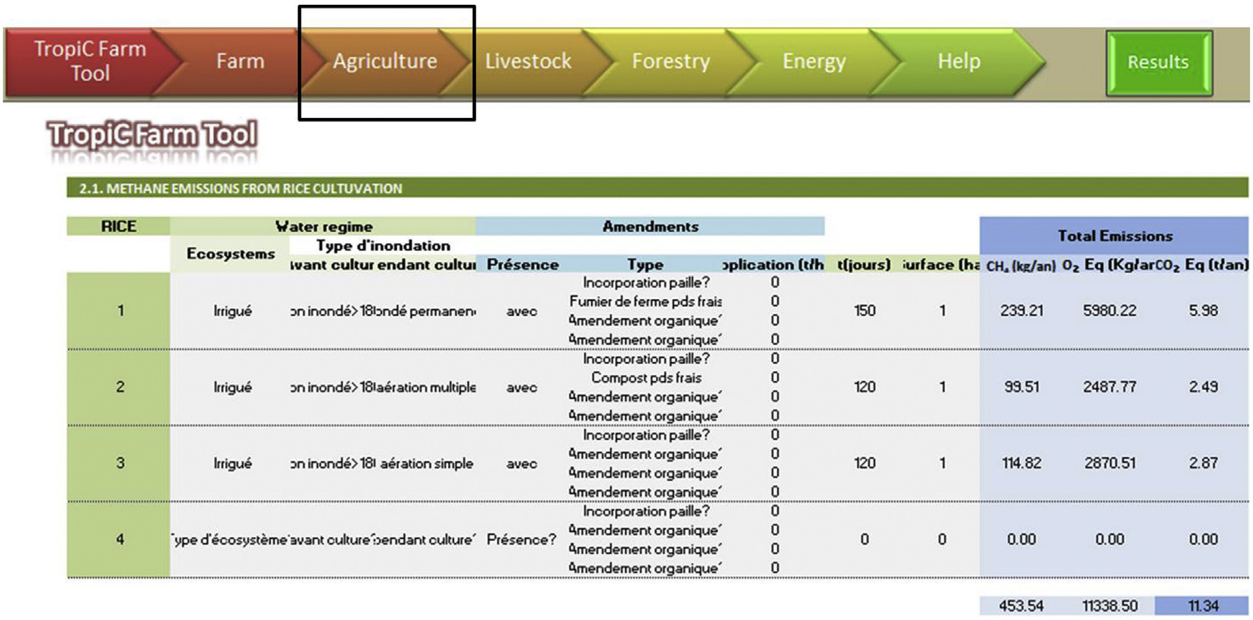

RICE	Water regime: Ecosystems	Type d'inondation: avant cultur	endant cultu	Amendments: Présence	Type	pplication (t/h	t(jours)	urface (ha	Total Emissions: CH4 (kg/an)	O2 Eq (Kg/ar	CO2 Eq (t/an)
1	Irrigué	on inondé> 18	ondé permanen	avec	Incorporation paille? / Fumier de ferme pds frais / Amendement organique / Amendement organique	0 / 0 / 0 / 0	150	1	239.21	5980.22	5.98
2	Irrigué	on inondé> 18	aération multiple	avec	Incorporation paille? / Compost pds frais / Amendement organique / Amendement organique	0 / 0 / 0 / 0	120	1	99.51	2487.77	2.49
3	Irrigué	on inondé> 18	aération simple	avec	Incorporation paille? / Amendement organique / Amendement organique / Amendement organique	0 / 0 / 0 / 0	120	1	114.82	2870.51	2.87
4	ype d'écosystème	avant culture	pendant culture	Présence?	Incorporation paille? / Amendement organique / Amendement organique / Amendement organique	0 / 0 / 0 / 0	0	0	0.00	0.00	0.00
									453.54	11338.50	11.34

Fig. 2. TropiC Farm Tool.

interviews and from results of CFP calculation. Ascending hierarchical classification using Ward aggregation method and considering Euclidean distance was performed to classify the 192 farms in different clusters (Marcotorchino and Michaud, 1982). For this, XLstat 2008 was used.

The variables considered for this classification were: the number of tree planted including all forestry and agroforestry species, the annual quantity of compost produced by each farmer, and the surface of land converted to SRI. Variation of farms CFP between clusters was compared using Kruskal-Wallis test once data was transformed to obtain positive value of CFP.

Data transformations are presented in the equations bellow:

$$\text{CFP expressed in tCO2 eq.ha}^{-1}\cdot\text{yr}^{-1}\text{: } Y = X + 17.48 \quad (7)$$

$$\text{CFP expressed in tCO2 eq.t}^{-1}\cdot\text{yr}^{-1}\text{: } Y = X + 11.6 \quad (8)$$

where X is the original value of CFP which could be positive or negative; Y corresponds to the CFP in positive value after adding a coefficient to the original value.

3. Results

3.1. Carbon footprint of farms

The average CFP of the 192 farms reached $0.8tCO_2eq.ha^{-1}\cdot yr^{-1}$ in terms of land surface and $0.1tCO_2eq.t^{-1}\cdot yr^{-1}$ in terms of crop production. Farms CFP decreased significantly when agroecological practices adoption increased. Agroecological practices integrated at farm scale reduced significantly farms CFP up to 364% in terms of land surface and up to 578% in terms of food production (Fig. 3; $p < 0.0001$). The highest CFP value occurred in cluster 1 which represented the most GHG emitting farms ($1.9\ tCO_2eq.ha^{-1}\cdot yr^{-1}$ and $0.5\ tCO_2eq.t^{-1}\cdot yr^{-1}$) whilst the lowest average farms CFP were in cluster 4; this last group represented the most GHG sequestering farms ($-4.9\ tCO_2eq.ha^{-1}\cdot yr^{-1}$ and $-2.2\ tCO2eq.t^{-1}\cdot yr^{-1}$). Actually when farms adopted more agroecological practices, their CFP decreased and might even have a negative value.

3.2. GHG sources and sinks at farm scale

The results showed that livestock, soil management and irrigated rice cultivation were the main sources of GHG at farm scale. N_2O emission from soil management represented about 25% of the total emissions while: CH_4 emission from irrigated rice, GHG emission from manure management and CH_4 emission from animal enteric fermentation counted respectively 24%, 24% and 23%. The energy consumption (fossil and renewable), the use of pesticides and chemical fertilizers produced a significantly lower emissions. In terms of sequestration, woody biomass and cropland soil were the main sinks of GHG at farm scale. Carbon removal in woody biomass accounted about 56% of total GHG removal at farm scale while carbon removal in cropland soil accounted about 44% (Fig. 4).

3.3. Comparison between farms CFP using Tier 1 and Tier 3 factors for carbon removal in woody biomass and in cropland soil

The results showed that for the overall 192 farms studied, the

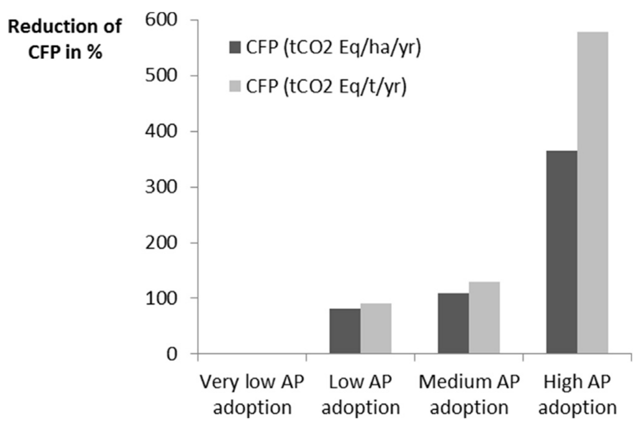

Fig. 3. Contribution of AP adoption to farms CFP reduction.

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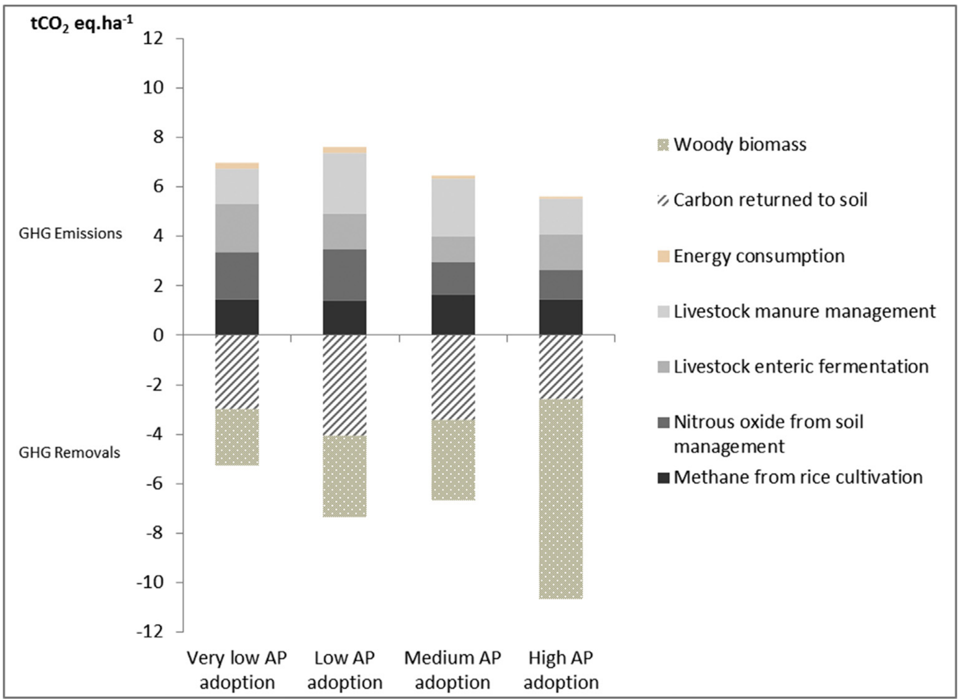

Fig. 4. Contribution of practices to farms CFP.

use of Tier 3 factors reduced significantly farms CFP compared to the use of Tier 1 factors (Table 5, $p < 0.0001$).

This study allowed us to say that Tier 1 factors for carbon removal in woody biomass and cropland soil underestimated the GHG removals into sinks. It demonstrated the crucial need of Tier 3 factors for a more accurate CFP calculation. Later on, if the deal about carbon cost under the carbon market involves Malagasy farmers, it will be better to consider Tier 3 factors than Tier 1 for carbon removal in woody biomass and cropland soil.

4. Discussion

4.1. Comparison with similar studies in different contexts

In terms of land surface and total crop production, farms CFP was estimated in average to be 0.8 $tCO_2eq.ha^{-1}\cdot yr^{-1}$ and 0.1 $tCO_2eq.t^{-1}\cdot yr^{-1}$.

These results showed that farms CFP in Itasy region were 80% lower than farms CFP in other developing countries. For instance, in

Table 4
Description of each cluster of farms.

	Cluster 1				Cluster 2				Cluster 3				Cluster 4			
Number of farms	120				44				10				18			
Agroecological practices adoption	Very low adoption				Low adoption				Medium adoption				High adoption			
	Mean	Min	Max	Median	Mean	Min	Max	Median	Mean	Min	Max	Median	Mean	Min	Max	Median
Trees (number)	55	0	356	18	138	0	660	92	**783**	6	2513	724	**1192**	592	2040	1167
Compost (t yr^{-1})	0.4	0.0	2.4	0.0	3.7	0.0	8.5	3.7	**11.4**	7.5	18.4	10.5	2.4	0.0	5.3	2.2
SRI (ha)	0.0	0.0	0.2	0.0	0.2	0.0	1.0	0.1	0.2	0.0	1.0	0.1	0.0	0.0	0.5	0.0
Land surface (ha)	1.0	0.0	6.6	0.8	1.5	0.2	6.0	1.1	3.2	1.4	6.8	2.7	3.2	0.6	11.8	2.6
Main productions (t yr^{-1})																
Rice	1.5	0.0	17.0	1.0	2.6	0.4	9.4	2.2	5.9	1.0	20.2	4.1	3.6	0.4	9.6	3.6
Maize	0.2	0.0	2.0	0.1	0.5	0.0	4.6	0.2	0.8	0.0	4.9	0.1	0.9	0.0	7.7	0.3
Cassava	1.0	0.0	22.5	0.5	1.3	0.0	6.6	0.5	2.5	0.0	6.1	1.8	2.0	0.0	13.0	0.4
Bean	0.0	0.0	0.4	0.0	0.1	0.0	1.3	0.0	0.6	0.0	2.2	0.3	0.2	0.0	1.3	0.1
Tomato	0.3	0.0	5.0	0.0	0.7	0.0	7.5	0.0	1.4	0.0	5.0	0.5	2.9	0.0	14.5	0.7
Organic fertilizer (t yr^{-1})																
Cattle manure	**1.9**	0.0	10.0	1.6	**2.5**	0.0	15.0	0.9	**6.8**	0.0	28.8	4.2	**4.9**	0.0	16.0	3.8
Pig manure	0.2	0.0	2.5	0.0	0.1	0.0	0.8	0.0	1.0	0.0	4.0	0.3	0.3	0.0	2.2	0.0
Chemical fertilizer (kg yr^{-1})																
Urea	0.9	0.0	50.0	0.0	0.7	0.0	10.0	0.0	5.0	0.0	50.0	0.0	1.6	0.0	20.0	0.0
NPK	5.1	0.0	80.0	0.0	5.6	0.0	90.0	0.0	7.2	0.0	20.0	3.3	12.2	0.0	75.0	0.0
Livestock (head)																
Cattle	**2**	0	16	2	**2**	0	14	1	**5**	0	14	4	**4**	0	11	3
Pig	1	0	12	1	1	0	8	0	5	0	28	1	2	0	10	1

SRI: System of Rice Intensification; NPK: Nitrogen Phosphorus and Potassium.
Notable values which characterized clusters.

Table 5
Comparison of farms CFP using Tier 1 and Tier 3 factors for carbon removal in woody biomass and cropland soils.

	Tier1	Tier3
	CFP (tCO_2 eq yr^{-1})	CFP (tCO_2 eq yr^{-1})
Mean	2.77	0.37
Min	−27.71	−22.38
Max	26.03	16.45
Mediane	2.14	0.44

Kenya, farms CFP were reported to range between 4 and 6.5 $tCO_2eq.ha^{-1}\cdot yr^{-1}$ (Seebauer, 2014). Two reasons might explain these differences: the importance of GHG removals in woody biomass (2.24–8.07 $tCO_2eq.ha^{-1}\cdot yr^{-1}$) and in cropland soils (2.56–4.07 $tCO_2eq.ha^{-1}\cdot yr^{-1}$) in Itasy region farms and the high amount of GHG emissions from livestock enteric fermentation in Kenyan farms (8.2 $tCO_2eq.ha^{-1}\cdot yr^{-1}$) compared to Malagasy farms (1.06–1.95 $tCO_2eq\cdot ha^{-1}\cdot yr^{-1}$).

In emerging countries like China, CFP of crop production was estimated to be 2.86 $tCO_2eq.ha^{-1}\cdot yr^{-1}$ (0.78 $tCE.ha^{-1}yr^{-1}$) and 0.40 $tCO_2eq\cdot t^{-1}\cdot yr^{-1}$ (0.11 $tCE\cdot ha^{-1}yr^{-1}$) (Cheng et al., 2011). This value is 3.5 times higher than Malagasy farms CFP. In fact, it was stated that China crop production depended more on N fertilizer compared to Malagasy context.

In developed countries like Scotland, the average CFP for farms was estimated to be around 1.29 $tCO_2eq.\ ha^{-1}\cdot yr^{-1}$ (351.7 kg CE $ha^{-1}yr^{-1}$) (Hillier et al., 2009). Although this value is 1.61 times higher than Malagasy farms CFP, it is closer to organic farms CFP in the East of Scotland (Hillier et al., 2009). The reason may be that Malagasy farmers use only a low level of chemical and N fertilizers (4.9 kg $ha^{-1}\cdot yr^{-1}$).

These results indicate the low contribution of Malagasy smallholders to climate change compared to other farmers in other countries.

However, the diversity of methodologies and definitions of CFP in the literature constraints the comparison of results between published studies.

4.2. Contribution of practices to farms CFP

Nitrous oxide (N_2O) emissions from soil management represented up to 25% of all GHG emissions at farm scale (Fig. 4). This includes firstly the direct emissions from the process of nitrification and denitrification and secondly the indirect emissions through the process of volatilization, leaching and runoff of nitrogen (N). The increase of N added to soils from different sources such as synthetic N fertilizers, organic fertilizer (manure, compost) and crop residues induces an important amount of N_2O emissions from managed soils (IPCC, 2006). In the studied context, the high exploitation of lowlands for rice cultivation and vegetable crops which are the most fertilized crops, mainly by farmyard manure (more than 10 t ha^{-1}) explains the important N_2O emissions from soils at farm scale.

By using the IPCC (2006) emission factors, we found that the average N_2O emissions from soil management were estimated to be around $1.24tCO_2eq.ha^{-1}\cdot yr^{-1}$. This value is well above the measured annual N_2O emissions from Malagasy agricultural soils estimated to be $0.12tCO_2eq.ha^{-1}\cdot yr^{-1}$ (0.26 kg N ha^{-1}) (Chapuis-Lardy et al., 2009). This indicates the need to undertake more measurements on GHG fluxes in different agro systems to get CFP values closer to the field reality.

Methane emissions from irrigated rice cultivation represented up to 24% of total GHG emissions at farm scale. This is due to the anaerobic decomposition of organic matter in flooded rice (IPCC, 2006). The amount of CH_4 emitted depends on different parameters such as the grown crops duration, the water regimes before and during cultivation period, and the organic soil amendments (IPCC, 2006).

Different mitigation technologies were proposed to reduce the CH_4 emissions from irrigated rice (Smith et al., 2008); those include alternating flooding/drying once or several times during the growing season (Wang et al., 2000; Yan et al., 2003). In Itasy region, the system of rice intensification (SRI), allowing water regime control, reduced CH_4 emissions up to 50%, while in China, the local irrigation practice of drying at midseason reduced CH_4 emission rates by 23% compared to continuous flooding (Wang et al., 2000). Due to this great potential of CH_4 emission reduction and taking into account the benefits it provides in terms of crop yield, the SRI is recommended as a suitable mitigation practice to be adopted by farmers.

Livestock is the third important source of GHG at farm scale due to the manure management (24%) and the enteric fermentation (23%). In Malagasy context, cattle management follows traditional ways. The local breed, characterized by a low productivity does not offer many options of improved feeding practices to reduce CH_4 emission. Adding more concentrates to cattle feeds in order to reduce CH_4 emissions (Lovett et al., 2003a,b) would not be suitable for farmers because of financial cost. However, manure management can be improved by replacing stockpiling to composting. In terms of GHG flux, composting rather than stockpiling manure allows GHG emissions reduction (Pattey et al., 2005). In Itasy region, composting manure and organic matter is one the AP proposed to farmers in order to improve their soil fertility. Even if the majority of farmers adopt the traditional stockpiling manure, the composting adoption rate progressively increases in the studied region during the last 5 years.

GHG emissions from other farm activities such as use of pesticides, chemical fertilizers and energy consumption remain very low because Malagasy farming systems are characterized by a very low use of inputs (Randrianarisoa and Minten, 2003).

4.3. Influence of agroecological practices on CFP reduction

Results showed that farms CFP did not depend on farm size (total land surface) but on farm activities and practices. Small and large farms could be both GHG emitting or GHG sequestering (Fig. 6a). The diversity of practices and activities between farms were the main cause of CFP variability.

Trees planting whether in agroforestry or in forestry system was significantly the most influencing agricultural practice causing CFP variability between different clusters ($p < 0.000000$).

Agroforestry and forestry represented 38% of farms land surface, sequestering 1.3 MgC ha^{-1} yr^{-1}, and corresponding to $4.7tCO2eq.ha^{-1}$ yr^{-1}. After 20 years of trees plantation, carbon sequestration in woody biomass was estimated to be 26 MgC ha^{-1}. This value is between 12 and 228 MgC ha^{-1} which was the estimated carbon sequestration potential in tropical agroforestry systems (Albrecht and Kandji, 2003). These results showed the importance of AP adoption like agroforestry and forestry in reducing farms CFP.

In cluster 1 and cluster 2, where farm had respectively very low and low levels of AP adoption, farms CFP indicated in average GHG emitting farms. In cluster 4 (high level of AP adoption) results showed GHG sequestering farms because of the significant carbon sequestration through tree plantation (Figs. 4 and 5). Results showed that, the GHG removals in woody biomass reduced significantly ($p < 0.0001$) farms CFP compared to GHG removals in soils. Thus, without agroforestry and forestry systems, farms would be almost GHG emitting (Fig. 6b and c).

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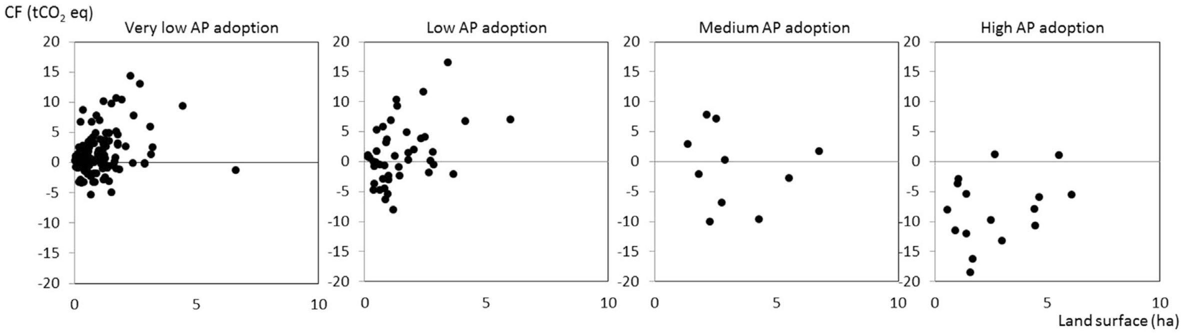

Fig. 5. Distribution of farms CFP according to various levels of AP adoption and farm land surface.

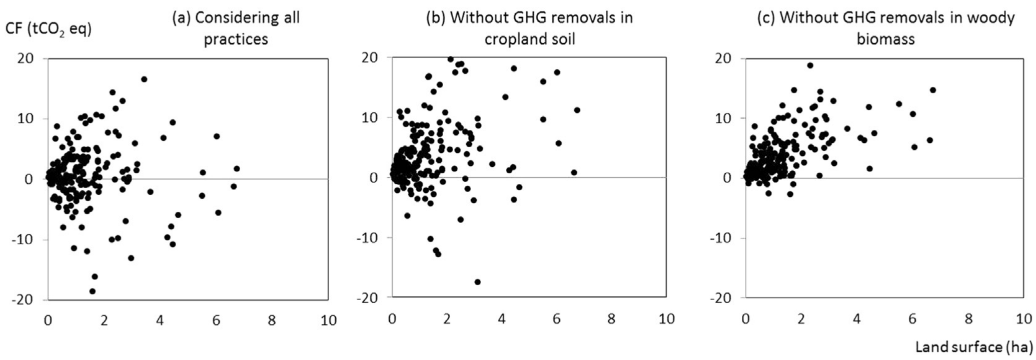

Fig. 6. Farms CFP according to various scenarii of sequestration practices and farm land surface.

Farms CFP variation were firstly caused by GHG removals in woody biomass, and then by GHG emission from livestock enteric fermentation and manure management. The impact of composting organic matters and SRI on farms CFP reduction was less significant because of its low level of adoption.

Given the important contribution of these AP to CFP reduction, the implementation of these mitigation practices should be strengthened to assist farmers.

In the studied context, the agroecological practices were progressively adopted by farmers; the cluster 3 and cluster 4, representing the richest farms, adopted the most these concepts. This is mainly explained by the fact that richest farmers own more land for tree plantations and agricultural labour mean required for the SRI and composting implementation. Therefore, more technical and financial support should be provided to poorest farmers.

This study is innovative and differs from previous ones by its “farm scale” approach which considers the whole farm as a unit. This approach encourages more the farmers to adopt cleaner practices as results directly reflect the carbon impact of their activities.

Tropical Farm Tool, the calculator developed in the current work can also be used in other studies with similar climate conditions to Madagascar.

Furthermore, the comparison between the use of Tier 1 and Tier 3 methods showed a considerable gap between farms CFP values. The use of Tier 1 method overestimated up to 7 times higher the farms CFP compared to the use of Tier 3 method. This indicates the areas of uncertainty of the IPCC estimates which confirms the need of further field measurements of GHG emission/removal according to each context. Other studies focused on GHG fluxes quantification have proved it (Chapuis-Lardy et al., 2009; Yan et al., 2003).

According to previous results and considering the studied context, two main areas of strategic development are proposed. The first one consists to strengthen the support to farmers in the implementation of AP (planting trees, adoption of compost and SRI). More technical and financial support should be provided to the poorest farms with low means of production. This implies the continuity of the different actions and development projects of local NGOs. The second area involves the development of further scientific research focusing on the GHG flux measurement in the tropical and Malagasy agricultural context. Indeed, the scarcity of GHG emission factors appropriate to tropical contexts constrained to systematically use the default values (Tier 1) that reduced significantly the precision of CFP calculation (Plassmann et al., 2010).

5. Conclusion

The smallholder farms in Itasy region showed lower CFP compared to CFP of crop productions and farmers in developed, emerging and some developing countries. This was mainly due to the importance of GHG removals in woody biomass and to the very low use of N fertilizers in Malagasy farming systems. The integration of agroecological practices at farm scale such as agroforestry and forestry systems allowed a significant reduction of farms CFP up to 364% in terms of land surface and up to 578% in terms of food production which mean an important GHG sequestration at farm scale. The use of Tier3 method compared to Tier 1 method reduced significantly farms CFP. That indicates the need of more GHG fluxes measurements adapted to each context to reduce the area of uncertainty of the IPCC default values.

This study highlighted the low contribution of Malagasy smallholder farms to climate change and the GHG mitigation potential of AP integrated at farm scale.

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