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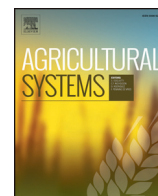
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Environmental and economic impacts of agri-environmental schemes designed in French West Indies to enhance soil C sequestration and reduce pollution risks. A modelling approach



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ABSTRACT

Agri-environmental schemes (AESs) are the main public policy instrument used in Europe to encourage farmers to adopt environmentally-friendly farming practises. Some AESs designed in French West Indies to replace N fertilizers with composts to reduce nitrate pollution and enhance C sequestration have been unsuccessful because few farmers adopted them despite the subsidies offered for the provision of environmental benefits. To explain this low adoption rate, we assessed the agri-environmental and economic impacts of two AESs and compare them with the most widely-applied strategy based on inorganic N fertilizer (NFER), and with an organic strategy based on sewage sludge (SLUD), a free organic amendment. The first AES was proposed in 2007 (AES_{old}) and only concerned with the use of composts. The second was proposed in 2014 (AES_{new}) and combines the use of composts and inorganic N fertilizer at a rate 25% lower than NFER. The study was applied to water yam using a crop model to obtain agri-environmental indicators over a period of ten years, which were then used to calculate economic outputs for small and large farms. Although AES_{old} increased C sequestration by 300% and reduced nitrate leaching by 80% compared to NFER, it also reduced yields (13%) and net income for farmers (30%). The subsidy offered by AES_{old} did not compensate the loss of productivity, which explains its low rate of adoption. AES_{new} and SLUD increased C sequestration (350% and 400%) and reduced nitrate leaching (45% and 34%), and maintained yields and net income after five years of implementation. Yields and net income during the first five years were 5–10% lower than under NFER. Although the land area concerned by SLUD is limited because of regulatory constraints, AES_{new} could be a satisfactory policy instrument in French West Indies because it promotes environmental benefits and maintains economic income in the medium term for smallholder using family labour. The economic performance of AESs was lower for large farms; the adoption rate could be improved for these farmers through the implementation of mechanization to reduce labour costs. For both farm types, it may be necessary to increase subsidies during the first five years to offset yield losses during this period and the fixed and transition costs attached to adoption.

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1. Introduction

Because of the depletion of fossil energy resources, the increase in greenhouse gas (GHG) emissions and water contamination due to nitrate leaching, replacing inorganic fertilizers with organic amendments in agriculture has been explored as a means of managing soil fertility in a more sustainable manner (Dogliotti et al., 2014). In French West Indies, French Overseas Departments located in the Caribbean, agriculture has been intensified during the past three decades and has caused widespread environmental damage. The use of systematic ploughing and monocropping, together with high rainfall intensity and the application of high rates of pesticide and inorganic fertilizers, are the principal factors causing soil degradation and pesticide and nitrate leaching

(Cattan et al., 2009; Charlier et al., 2009). A recent GHG inventory carried out in French West Indies indicated that nitrogen (N) fertilizers and lime spreading ranked second after enteric fermentation among the most important causes of GHG emissions (Colomb et al., 2014). This situation is particularly critical insofar as climate change combined with intensive agricultural practises may lead to a decrease in soil organic matter content and then an increase in CO₂ emissions (Sierra et al., 2010). Orienting farmers toward the use of organic amendments may therefore be a means of reducing the negative environmental impacts of agriculture.

Although farmers in French West Indies have traditionally used organic inputs – mainly manure – to manage soil fertility, at present most of them are tending toward the use of inorganic inputs (Cattan et al., 2009; Clermont-Dauphin et al., 2004). Because of the low adoption rate of organic amendment in French West Indies, several agri-environmental schemes (AESs) have been implemented specifically to

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motivate farmers to make this switch (FEADER, 2012). Agri-environmental schemes are the principal public policy instrument used in Europe to increase the willingness of farmers to adopt environmentally-friendly practises (Espinosa-Goded et al., 2013). They are designed to compensate farmers for losses of economic productivity and encourage them to switch to environmentally-friendly practises. AESs may be designed at the local level so that they can be adapted to specific environmental conditions as in the Caribbean. Concerning organic amendment, the AES proposed in French West Indies included a subsidy for farmers associated with an undertaking to reduce the use of industrial chemical inputs and apply compost in their fields so as to increase carbon (C) sequestration and reduce nitrate leaching (FEADER, 2012). Despite this economic compensation this AES has proved unsuccessful; only a few farmers have signed up for this measure, representing less than 2% of agricultural land.

The adoption of AES in Europe has been investigated by several authors. These studies showed that poor institutional organization, high fixed and transaction costs and the intensity of technical change are key factors for the adoption of AES (Barreiro-Hurlé et al., 2010; Espinosa-Goded et al., 2013; Mettepenningen et al., 2013). In French West Indies, extension agents have reported that low adoption rates might be explained by the lack of information concerning the benefits associated to the use of organic amendments (Board of Food, Agriculture and Forestry, pers. comm.). However, several farm surveys have indicated that 20% of farmers use organic amendments such as sewage sludge and manure (Sierra et al., 2015), which suggests that farmers are interested in using organic amendments but are preferentially orientated toward freely-available amendments. Therefore, in order to ensure that AES is more efficient at the landscape scale, a more detailed analysis of the performance of organic amendment strategies needs to be carried out. This should help policy makers to design new AESs under tropical conditions that are more appropriate from the environmental and economic points of view.

In this paper, we propose an agri-environmental and economic approach to assess the performance of the AES. We therefore compared two AES scenarios with the most current practise which includes only inorganic fertilizers, and with an organic practise that includes the use of sewage sludge. This comparison of the scenarios and their accompanying policies was performed using agri-environmental and economic indicators. The study focused on water yam crop (*Dioscorea alata* L.) because this is the leading food crop grown in French West Indies. Crop performance was assessed using a biophysical model adapted to the soil-crop-climate conditions of French West Indies, and the results were used to calculate the economic outputs in small and large farms and to propose more efficient policy options.

2. Materials and methods

2.1. Rationale of the study

This study involved three steps: (i) determination of the humification factor of two organic amendments (sewage sludge and compost) in order to evaluate their contribution to soil C sequestration, (ii) simulation of the performance of the soil-climate-yam system under different scenarios for organic amendment and inorganic fertilizer inputs, and the assessment of agri-environmental indicators, and (iii) assessment of economic indicators based on the results obtained in step (ii). The AESs analysed in this study were designed to be applied in soils with relatively low levels of organic matter (i.e. C content $\leq 20.0 \text{ mg C kg}^{-1}$; DAAF, 2007); in this way, only acid ferralsols are concerned by this policy scheme. So, the first and the second steps of our analysis were performed in the context of an acid ferralsol using the soil parameters reported in a previous study (Sierra et al., 2010). Some characteristics of this soil are presented in Table 1.

The humification factor of sewage sludge and compost was estimated from laboratory experiments and then integrated in the CropSyst-

Table 1

Some characteristics of the soil and organic amendments used in the laboratory experiment and in model simulations.

	pH	C g kg ⁻¹	N	C/N
Soil	5.1	20.0	2.1	9.5
Compost	6.3	201.3	11.8	17.0
Sewage sludge	6.5	372.6	64.2	5.8

Yam model (Marcos et al., 2011), which was used to simulate soil-climate-yam behaviour. The scenarios tested were: (i) inorganic N fertilizer applied at a rate of $200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (scenario NFER), (ii) organic amendment applied as compost at a rate of 15 Mg fresh matter $\text{ha}^{-1} \text{ yr}^{-1}$ (equivalent to $80 \text{ kg organic N ha}^{-1} \text{ yr}^{-1}$) (AES_{old} scenario), (iii) organic amendment applied as compost at a rate of 7 Mg fresh matter $\text{ha}^{-1} \text{ yr}^{-1}$ (equivalent to $37 \text{ kg organic N ha}^{-1} \text{ yr}^{-1}$) and N fertilizer applied at a rate of $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (AES_{new} scenario), and (iv) organic amendment applied as sewage sludge at a rate of 20 Mg fresh matter $\text{ha}^{-1} \text{ yr}^{-1}$ (equivalent to $190 \text{ kg organic N ha}^{-1} \text{ yr}^{-1}$) (SLUD scenario). The NFER scenario corresponded to the practise most widely applied by farmers in French West Indies and was used as the reference in this study. The AES_{old} scenario corresponded to the AES proposed in French West Indies for the 2007–2013 period (DAAF, 2007). The AES_{new} scenario corresponded to the AES proposed for the 2014–2020 period (DAAF, 2014), while the SLUD scenario corresponded to the practise applied by about 15% of yam growers, where the rate of sewage sludge matches the maximum annual rate set by French regulations (e.g. equivalent to $3 \text{ Mg dry matter ha}^{-1}$; Journal Officiel de la République Française, 1998).

Six indicators were evaluated in order to compare the scenarios: C sequestration, nitrate leaching, crop yield, labour time necessary for the application of inorganic and organic inputs, total cost of these inputs and net income for the farmer. Net income was calculated using the Igmarnage software program (Causeret et al., 2012).

2.2. Assessment of the humification factor of the organic amendments

The compost assessed during this study was produced at the Sita Verde industrial composting facility in French West Indies and obtained using bagasse blended with sugar scum. The aerobically digested sludge was obtained from the Jarry wastewater treatment plant in French West Indies. Some characteristics of the compost and sewage sludge are presented in Table 1. The laboratory experiment was carried out as described by Sierra et al. (2013). Briefly, soil and organic amendment were mixed thoroughly, placed in glass vials and incubated at $30 \text{ }^\circ\text{C}$ in the dark for 16 weeks. A treatment without organic amendment (control soil) was also included. The mineral N and C–CO₂ produced during incubation were measured 15 times during the experiment using 4 replicates. Carbon and N mineralizations from organic amendments were calculated on the differences between the soil-amendment treatments and the control soil. The time course of cumulated C and N mineralizations was fitted using the model proposed by Nicolardot et al. (2001) to estimate the turnover of organic inputs in soil. This model assumes that the decomposed organic amendment is either mineralized or assimilated by the microbial biomass. Thereafter, the microbial biomass decay produces both humification (sequestration in soil organic matter) and secondary mineralization. Therefore, the model is able to estimate C and N humifications from data of C and N mineralizations.

2.3. Simulation of the performance of the soil-yam system

CropSyst-Yam is a multi-year crop model that simulates the crop development and growth of water yam, soil-crop-climate interactions, changes in soil water and C and N balances during crop rotation (Marcos et al., 2011). This model was calibrated and tested from

experimental data obtained in field studies carried out using the current practises applied by farmers in French West Indies. Yam development is estimated as a function of the observed photoperiod and air temperature. Yam growth depends on C partitioning into each plant part according to C and N availability and is controlled by crop development. During the vegetative phase, the roots, leaves and stems are the dominant sinks for C, while tubers are the dominant sinks after tuber initiation. Model parameters used to simulate plant development and growth were those reported by Marcos et al. (2011). Soil C and N dynamics are controlled by the turnover of organic amendments and crop residues, which is affected by their C/N ratio, and soil moisture and temperature calculated by the model. The decomposition of soil organic matter is controlled by soil moisture and temperature. The model parameters for soil C and N turnover included in the model were those reported by Sierra et al. (2010), which were obtained from field studies carried out for the same ferralsol as that used in this study. Further details of the model can be found in Marcos et al. (2011).

The model was run using weather records for the 2001–2010 period obtained from the Duclos Experimental Station of the Institut National de la Recherche Agronomique in Guadeloupe (French West Indies) (16° 12'N, 61° 39'W, 250 m a.s.l.). Photoperiod data was that reported by Marcos et al. (2011) for the latitude of Guadeloupe. Weather data included daily maximum and minimum air temperatures, global radiation and daily rainfall. At this site, the mean annual air temperature is 25.5 °C and the mean annual rainfall is 2500 mm, which are representative of the climate for the region where ferralsols are present in French West Indies. Crop management simulated with the model was set at that used by yam growers (Barlagne, 2014), with a planting date on May 15 each year. For the NFER and AES_{new} scenarios, two-thirds of the N fertilizer was applied at planting and one third 40 days after planting. The compost under the AES_{old} and AES_{new} scenarios, and the sewage sludge in the SLUD scenario were applied one week before planting. Plant density was set at 24,000 plants ha⁻¹ for all the scenarios, and the crop was unstaked. Irrigation was not applied. We assumed that weeds, plant diseases and insects were controlled as currently made by farmers in French West Indies, and then these factors did not limit crop yield. Similarly, we considered that phosphorus and potassium were applied at the current rates (i.e. 60 kg P ha⁻¹ and 150 kg K ha⁻¹) and did not limit crop yield. These assumptions were based on the field studies reported by Marcos et al. (2011) for yam crops in French West Indies.

Carbon sequestration was calculated by subtracting the initial soil organic C stock (Table 1) from the stocks estimated by the model at the end of the simulated period. Nitrate leaching and crop yield for each year were obtained directly from model outputs.

2.4. Economic indicators

The labour time required for the application of inorganic and organic inputs, their cost and net income for the farmer were estimated using Ignamarge software (Causeret et al., 2012). Ignamarge is a program implemented in MS Excel which calculates the technical and economic performance of yam cropping systems as a function of farming practises, crop yield and economic parameters. The model is designed to estimate yam production outputs while calculating technical and economic performance and simulating the impact of technical or economic changes (e.g. innovations in production modes, changes in market prices or subsidies). The inputs are the crop management system (e.g. type and timing of farming practises, amount of inorganic and organic inputs, labour time), farm characteristics (e.g. cultivated area), selling prices, subsidies and yields. The last was obtained from the CropSyst-Yam model. The parameter values included in Ignamarge were obtained from several surveys carried out in French West Indies, which involved both farmers and agricultural extension services (Barlagne, 2014). Ignamarge was parameterized to represent the most common cropping system in French West Indies. The values of the principal parameters

used to estimate technical and economic performance are presented in Table 2. Model outputs used in this study were gross and net income, total labour time, total cost of fertilizer and compost inputs, and total cost of other farming practises. Calculations of net income included the subsidies offered by the AES for the provision of environmental benefits (i.e. 900 € ha⁻¹ yr⁻¹; Table 2). No subsidies are actually offered for the NFER and SLUD scenarios.

2.5. Estimate of the impact of the farm size

In order to have a representative view of the farming context of yam cultivation in Guadeloupe, we considered in our analysis two types of farm. Simulations were performed for large (>1 ha) and small (≤1 ha) farms. The size of the plots devoted to water yam varies from 1 ha to 2 ha in large farms and from 0.1 ha to 1 ha in small farms (Barlagne, 2014). Surveys carried out by Barlagne (2014) indicated that crop management and yields were similar for both farm types. This author reported that the main difference between farms involved the type of labour: family labour in small farms and seasonal-wage labour in large farms. Therefore, we assumed that simulations carried out with the crop model and the results obtained for crop yield, C sequestration and nitrate leaching were applicable to both farm types. So, only economic parameters and calculations were adapted for each farm type (Table 2). For large farms the cost of seasonal-wage labour was set at 10 € h⁻¹; the cost of family labour in small farms was considered as being nil. The cost of seasonal-wage labour for large farms was included in all the farming practises; i.e. soil tillage, fertilizer and compost application, seed yam preparation, planting, weeding, pest control and harvest.

3. Results

3.1. Compost and sewage sludge decomposition in soil

Fig. 1 presents C and N mineralization from compost and sewage sludge obtained under laboratory conditions. The results are expressed relative to the added C and N in order to simplify the comparison between organic amendments with different C and N contents (Table 1). Carbon mineralization for the compost occurred rapidly at the beginning of the experiment and decreased abruptly after two weeks of incubation (Fig. 1a). The decrease in the C mineralization rate over time was smooth for the sewage sludge. Nitrogen mineralization was small for the compost and was higher for the sewage sludge throughout the experiment (Fig. 1b). The model of Nicolardot et al. (2001) satisfactorily described C and N mineralization for both organic amendments; e.g.

Table 2

Technical and economic parameters used to calculate net income for farmers.

Parameter	Unit	Value
Labour time for amendment application ^a	h Mg ⁻¹	6.7
Labour time for fertilizer application ^a	h Mg ⁻¹	5.0
Cost of labour (large farms) ^b	€ h ⁻¹	10.0
Cost of labour (small farms) ^b	€ h ⁻¹	0.0
Selling price of yam tubers	€ Mg ⁻¹	2000
Subsidy offered for each agri-environmental scheme ^c	€ ha ⁻¹ yr ⁻¹	900
Cost of N fertilizer ^d	€ Mg ⁻¹	710
Cost of compost ^d	€ Mg ⁻¹	150
Other costs (large farms) ^e	€ ha ⁻¹ yr ⁻¹	16,844
Other costs (small farms) ^e	€ ha ⁻¹ yr ⁻¹	14,996

^a Manual application.

^b Corresponds to the cost of seasonal-wage labour in large farms. Small farms rely only on family labour where the cost was considered as being nil.

^c Corresponds to the subsidy offered for the provision of environmental services.

^d Includes the cost of the product and the transport to the farm.

^e Includes the cost of soil tillage, phosphorus and potassium fertilizers, seed yam preparation, planting, weeding, pest control and harvest. Labour cost is also included for large farms.

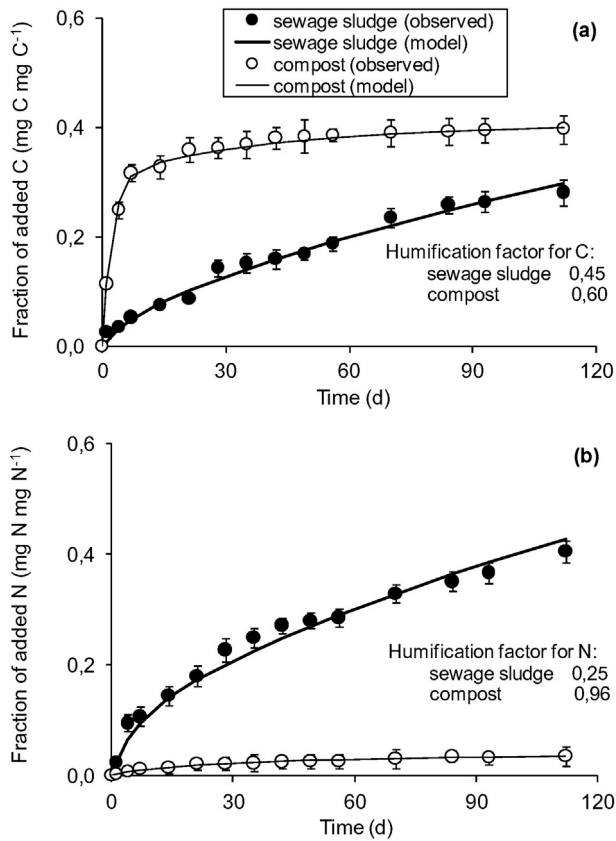


Fig. 1. (a) Carbon and (b) N mineralization from compost and sewage sludge determined during the laboratory experiment expressed as a fraction of the added C and N, respectively. Vertical bars indicate standard deviation ($n = 4$). The model refers to that proposed by Nicolardot et al. (2001).

for compost, $R^2 = 0.98$ for C and N, RMSE = 0.7; for sewage sludge, $R^2 = 0.98$ for C and N, RMSE = 5.3.

Indeed, the lower the overall rates of C and N mineralizations, the higher were the respective humification factors estimated with the model. In this sense, the model outputs indicated that C sequestration accounted for 60% of the initial C content for the compost and 45% for the sewage sludge. Nitrogen sequestration was 96% for the compost and 25% for the sewage sludge. These results indicate that C and mainly N sequestrations were much higher for the compost.

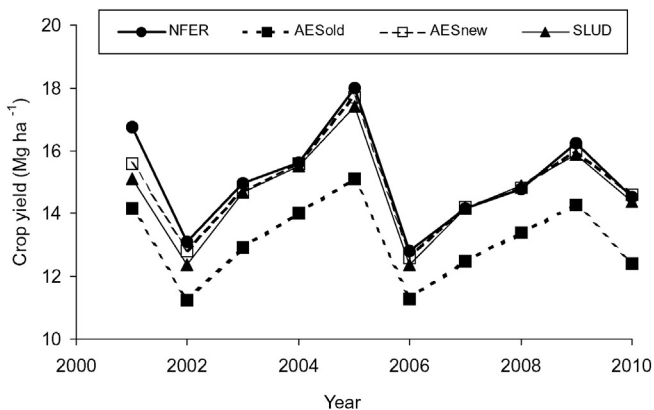


Fig. 2. Yam crop yields obtained by model simulations. Scenarios: NFER, N fertilizer applied at a rate of $200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; AES, agri-environmental schemes; AES_{old}, compost applied at a rate of $15 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$; AES_{new}, compost applied at a rate of $7 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$ and N fertilizer applied at a rate of $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; SLUD, sewage sludge applied at a rate of $20 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$.

3.2. Crop yield

Crop yield presented a relatively high variability between years (Fig. 2), and the coefficient of variation averaged 10% when considering all the scenarios. Under the NFER scenario, the difference in crop yield was 30% between the year with the highest yield (18 Mg ha^{-1} in 2005) and that with the lowest yield (13 Mg ha^{-1} in 2006). Crop yield was always higher under the NFER scenario but the differences between scenarios decreased over time. For example, the differences between NFER and AES_{new} averaged $0.7 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in 2001 and 2002, and $0.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in 2009 and 2010. The AES_{old} scenario displayed the lowest yields and the differences between it and NFER averaged $2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, which represented a 13% reduction in crop yield.

3.3. Nitrate leaching and C sequestration

Nitrate leaching presented a very high variability among years, with the coefficient of variation ranging from 61% for AES_{new} to 92% for AES_{old} (Fig. 3). Under the NFER scenario, nitrate leaching in 2003 and 2007 (i.e. $>200 \text{ kg N ha}^{-1}$) was higher than the rate of N fertilization applied to the crop. Nitrate leaching was always highest under that scenario and lowest under AES_{old}. The mean values over the 10 years of simulation were: $121 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for NFER, $80 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for SLUD, $66 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for AES_{new}, and $24 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for AES_{old}. Nitrate leaching was positively correlated ($P < 0.05$) with annual rainfall; e.g. $R^2 = 0.73$ for NFER, 0.66 for AES_{old}, 0.77 for AES_{new}, and 0.55 for SLUD, respectively. Rainfall ranged from 1700 mm in 2001 to 3800 mm in 2003.

The stock of soil organic C in the 0–0.25 m soil layer at the beginning of the simulated period was $52.5 \text{ Mg C ha}^{-1}$. At the end of that period the stock increased under all the scenarios: $52.9 \text{ Mg C ha}^{-1}$ in NFER, $53.9 \text{ Mg C ha}^{-1}$ in AES_{old}, $54.1 \text{ Mg C ha}^{-1}$ in AES_{new} and $54.2 \text{ Mg C ha}^{-1}$ in SLUD. So, C sequestration during the simulated period varied from 0.4 Mg C ha^{-1} in NFER to 1.7 Mg C ha^{-1} in SLUD (Fig. 4). C sequestration in SLUD represented an increase of 3% in the initial soil C stock. Differences in C sequestration between the AES scenarios were small: C sequestration was only 0.2 Mg C ha^{-1} higher under AES_{new} than under AES_{old}. Table 3 presents the relative contribution of organic amendments and crop residues to C sequestration under each scenario. Carbon coming from crop residues increased in line with the rise in crop yield and was higher for NFER and lower for AES_{old}.

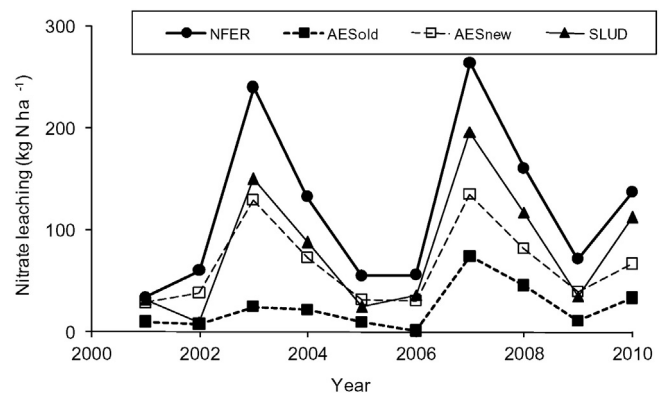


Fig. 3. Nitrate leaching over 10 years of the simulation. Scenarios: NFER, N fertilizer applied at a rate of $200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; AES, agri-environmental schemes; AES_{old}, compost applied at a rate of $15 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$; AES_{new}, compost applied at a rate of $7 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$ and N fertilizer applied at a rate of $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; SLUD, sewage sludge applied at a rate of $20 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$.

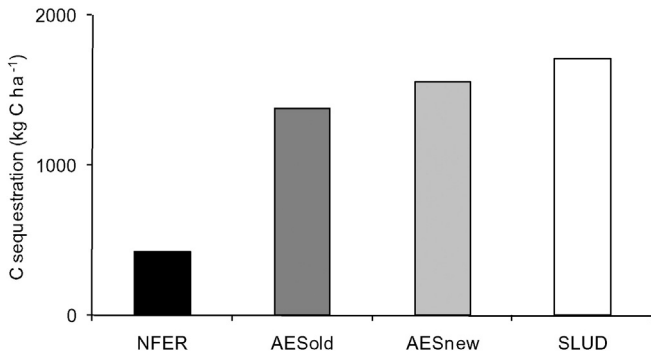


Fig. 4. C sequestration at the end of 10 years of simulation. Scenarios: NFER, N fertilizer applied at a rate of 200 kg N ha⁻¹ yr⁻¹; AES, agri-environmental schemes; AES_{old}, compost applied at a rate of 15 Mg fresh matter ha⁻¹ yr⁻¹; AES_{new}, compost applied at a rate of 7 Mg fresh matter ha⁻¹ yr⁻¹ and N fertilizer applied at a rate of 150 kg N ha⁻¹ yr⁻¹; SLUD, sewage sludge applied at a rate of 20 Mg fresh matter ha⁻¹ yr⁻¹.

3.4. Technical and economic indicators

Labour time associated to the application of N fertilizer and organic amendments increased in line with the increase in the rate of the organic amendment: 2 h ha⁻¹ yr⁻¹ for NFER, 48 h ha⁻¹ yr⁻¹ for AES_{new}, 100 h ha⁻¹ yr⁻¹ for AES_{old}, and 133 h ha⁻¹ yr⁻¹ for SLUD. Net income for large farms was lower than for small farms for all the scenarios, which was associated to a higher labour cost in the former (Table 4). The reduction in net income for large farms was lowest for NFER (-13%) and highest for AES_{old} (-29%). The high reduction in net income obtained for AES_{old} was linked to the labour cost associated to the application of a relatively high rate of compost. For this AES, neither the loss of gross income due to reduced yield (i.e. -3942 € ha⁻¹ compared with NFER) nor the additional cost for using compost (i.e. 1941 € ha⁻¹ and 2919 € ha⁻¹ for small and large farms, respectively) were offset by the subsidy offered for the provision of environmental benefits (Table 4). The situation was less restrictive for AES_{new} because crop yields and then gross income were less affected under this scenario.

Net income displayed a similar trend to that observed for crop yield (Fig. 5). Under NFER, net income varied by 50% between the year with the highest value (i.e. 20,695 € ha⁻¹ for small farms in 2005; Fig. 5a) and that with the lowest value (i.e. 10,344 € ha⁻¹ for small farms in 2006). The coefficient of variation of net income averaged 25% when considering all the scenarios. Differences between NFER and the other scenarios were greater for the first five years of the simulation and then decreased up to the end of the simulated period, mainly for small farms (Fig. 5a). For example, net income for small farms was on average 881 € ha⁻¹ yr⁻¹ higher under NFER than under AES_{new} for 2001–2005, and 213 € ha⁻¹ yr⁻¹ for 2006–2010. Differences in net income were small between AES_{new} and SLUD, mainly for small farms.

Table 3

Sources of C sequestration under the four scenarios. Scenarios: NFER, N fertilizer applied at a rate of 200 kg N ha⁻¹ yr⁻¹; AES, agri-environmental schemes; AES_{old}, compost applied at a rate of 15 Mg fresh matter ha⁻¹ yr⁻¹; AES_{new}, compost applied at a rate of 7 Mg fresh matter ha⁻¹ yr⁻¹ and N fertilizer applied at a rate of 150 kg N ha⁻¹ yr⁻¹; SLUD, sewage sludge applied at a rate of 20 Mg fresh matter ha⁻¹ yr⁻¹.

Parameter	Scenarios			
	NFER	AES _{old}	AES _{new}	SLUD
	%			
C from organic amendments	0	48	26	32
C from crop residues	100	52	74	68

4. Discussion

4.1. Biophysical performance of the soil-climate-yam system under the four fertilization strategies

Yam yield depended markedly on weather conditions and soil N availability. It is well known that yam is highly sensitive to rainfall distribution within the crop cycle. Marcos et al. (2011) found that yam yields in French West Indies decreased when high rainfall (e.g. >500 mm) occurred within 40 days of planting, because low global radiation during the vegetative phase affects development of the foliar surface and dry matter production. In the present study, this was the case in 2002 and 2006. On the other hand, a uniform distribution of rainfall between the vegetative and tuberisation phases explained the high yields observed in 2001, 2005 and 2009 (Fig. 2).

The effect of N availability on yam yield was mainly noticeable during the first five years when higher yields were obtained under the scenarios with higher rates of inorganic N fertilization (i.e. NFER and AES_{new}). After this, the differences between scenarios decreased because some of the N sequestered in soil organic matter from organic amendments was gradually released by mineralization under the AES_{new} and SLUD scenarios. During the second half of the simulated period, the NFER, SLUD and AES_{new} scenarios displayed a similar N availability, even though the N source differed partially between them (e.g. N from fertilizer and N mineralization from N sequestered in soil organic matter). Under the AES_{old} scenario, the small amount of N released from compost with a high sequestration rate, and the lack of N fertilizer, limited N availability and then crop yield. The crop yield gap between the NFER reference scenario and AES_{old} agreed with the results reported by de Ponti et al. (2012). By analysing a meta-dataset of 362 published studies on organic and conventional farming systems, these authors found that yields in organic systems were on average 80% those of conventional systems. This could be ascribed partially to the effect of soil N availability. For the AES_{old} scenario in the present study, a rate of 15 Mg ha⁻¹ of fresh compost with a humification factor for N equal to 0.96 (Fig. 1) was equivalent to only 3 kg N ha⁻¹ yr⁻¹ released during the crop cycle. This value was 144 kg N ha⁻¹ yr⁻¹ for sewage sludge under the SLUD scenario applied at a rate of 20 Mg ha⁻¹ yr⁻¹ and with a humification factor of 0.25. Such N availability for SLUD explains why yam yields under this scenario were similar to those obtained with AES_{new}. Indeed, the AES_{new} scenario improved yam yields obtained under AES_{old} and this was directly related to higher N availability during the crop cycle. This was due to both the application of inorganic N fertilizer and to a higher turnover of crop residues (Table 3). Interestingly, crop yields under the AES_{new} scenario were similar to those observed under NFER during the last five years of the simulated period. These findings suggest that this AES might be a suitable tool to encourage farmers to adopt environmentally-friendly farming techniques in the medium term.

The high levels of N leaching found during this study agreed with the results reported by other authors relative to cultivated soils in the humid tropics of the Caribbean (Cattan et al., 2009; Sierra et al., 2010). Although N leaching affected N availability under NFER, SLUD and AES_{new}, this effect was minor in terms of crop yield because the levels of available N in soil were sufficient to ensure crop nutrition under these scenarios. In fact, farmers in the Caribbean apply N fertilizers at rates which are about a third higher than crop requirements in order to overcome the effects of N leaching (Raphael et al., 2012). If account is taken that water drainage in the ferralsols of French West Indies corresponds to about 50% of rainfall (e.g. mean 1300 mm yr⁻¹; Sierra et al., 2010), N leaching of 120 kg N ha⁻¹ yr⁻¹ (mean value for the NFER scenario) would represent a mean concentration in the water table of about 10 mg N-NO₃ L⁻¹, which is much lower than the threshold defined by European regulations (i.e. 50 mg N-NO₃ L⁻¹; European Commission, 1991). However, such levels of N leaching may cause severe diffuse pollution and contribute to the degradation of coastal

Table 4
Economic calculations for small (≤ 1 ha) and large farms (> 1 ha) using the mean values of crop yields obtained for the simulated ten years period. NFER, N fertilizer applied at a rate of $200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; AES, agri-environmental schemes; AES_{old}, compost applied at a rate of $15 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$; AES_{new}, compost applied at a rate of $7 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$ and N fertilizer applied at a rate of $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; SLUD, sewage sludge applied at a rate of $20 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$.

Parameter	Small farms				Large farms			
	NFER	AES _{old}	AES _{new}	SLUD	NFER	AES _{old}	AES _{new}	SLUD
Gross income (€ ha^{-1}) ^a	30,195	26,253	29,720	29,341	30,195	26,253	29,720	29,341
Subsidy (€ ha^{-1}) ^b	0	900	900	0	0	900	900	0
Cost of fertilizer and organic amendments (€ ha^{-1}) ^c	309	2250	1282	0 ^d	331	3250	1765	1333
Other costs (€ ha^{-1}) ^e	14,996	14,996	14,996	14,996	16,844	16,844	16,844	16,844
Net income (€ ha^{-1})	14,890	9907	14,342	14,345	13,020	7059	12,011	11,164

^a Calculated using the mean crop yield and the selling price of yam tubers (see Table 2). We considered that these parameters were not affected by the farm type.

^b Corresponds to the subsidy offered for each AES. No subsidy is offered for NFER and SLUD.

^c Includes the cost of the product, the transport to the farm and the cost of application.

^d Within the framework of French regulations, sewage sludge is free of charge and the waste water treatment plant covers the cost of transport to the farm.

^e See Table 2 for the farming practises included in other costs.

resources (Charlier et al., 2009). In this sense, the SLUD and AES_{new} scenarios reduced N leaching by 35% and 45%, respectively, relative to NFER. This reduction was greatest with AES_{old} (80%) but at the expense of a significant reduction in N availability and crop yield.

The level of C sequestration estimated during this study was within the range of values measured by Feller et al. (2001) for soils of the Caribbean region; e.g. from $0.13 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ to $0.22 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Under the AES_{old}, AES_{new} and SLUD scenarios there were two sources of C and N sequestrations. The first was the direct contribution of C and N from the organic amendments, and the second was C and N derived from crop residues (Table 3). Therefore, even though C sequestration from compost under the AES_{old} scenario was greater

than that from sewage sludge under SLUD, total C sequestration was higher in the later case because of the larger quantity of crop residues (Fig. 4). For the same reason, C sequestration was slightly higher under AES_{new} than with AES_{old} even though the rate of compost application was much lower for the former. This agrees with the results reported by Diagana et al. (2007) relative to a tropical soil in Senegal. They observed that the use of inorganic N fertilizer together with crop residue incorporation resulted in a significant increase in soil C sequestration. However, despite the role of crop residues, the weak C sequestration under the NFER scenario found in the present study highlighted the difficulty encountered in stocking soil C in cultivated tropical soils when crop residues are the only C source. This result demonstrates the importance of the AESs focused on increasing the use of organic amendments in tropical regions.

Our results suggest that N availability played two major roles in the simulated soil–crop system, by affecting crop yield as well as the level of C sequestration through the amount of crop residues. With this in mind, it seems that AES_{new} and SLUD improved the NFER reference scenario in terms of C sequestration and reducing pollution risks due to N leaching, but they induced a slight decrease in crop yield, mainly during the first five years after initiation of the scenarios. The low crop yield obtained under AES_{old} is likely to be a major constraint regarding its acceptability to farmers.

4.2. Economic performance and policy implications for AES

Our study showed contrasted net income levels over time, which was linked to inter-annual variations in crop yields due to weather conditions. The high variability observed in net income could be a barrier to the adoption of innovations that require higher investment in work and inputs than that of current practises (Capalbo et al., 2004; Blazy et al., 2011). This was the case for AES_{old} in our study because it involves increased labour time and higher input costs, mainly in large farms. This fact and the lower net income observed for AES_{old} may therefore explain the low adoption rates of this AES observed during the 2007–2013 period. As mentioned above, subsidies offered by this AES did not compensate the reduction in gross income due to the loss of crop yield compared with the current scenario NFER, and this was more noticeable for large farms. Cropping systems in French West Indies are intensified, so there is a gap in economic performance between inorganic fertilization and organic amendment, and the subsidies available are insufficient to be viable. The situation may however differ for low input systems in other tropical regions, where the economic viability of organic amendment has been demonstrated, which was mainly associated to lower labour costs; e.g. Ouédraogo et al. (2001) for West Africa; Mekuria et al. (2013) for Laos.

The SLUD scenario involving the application of sewage sludge ensured good economic performance for smallholders and had a positive effect on soil organic matter, thus making it possible to

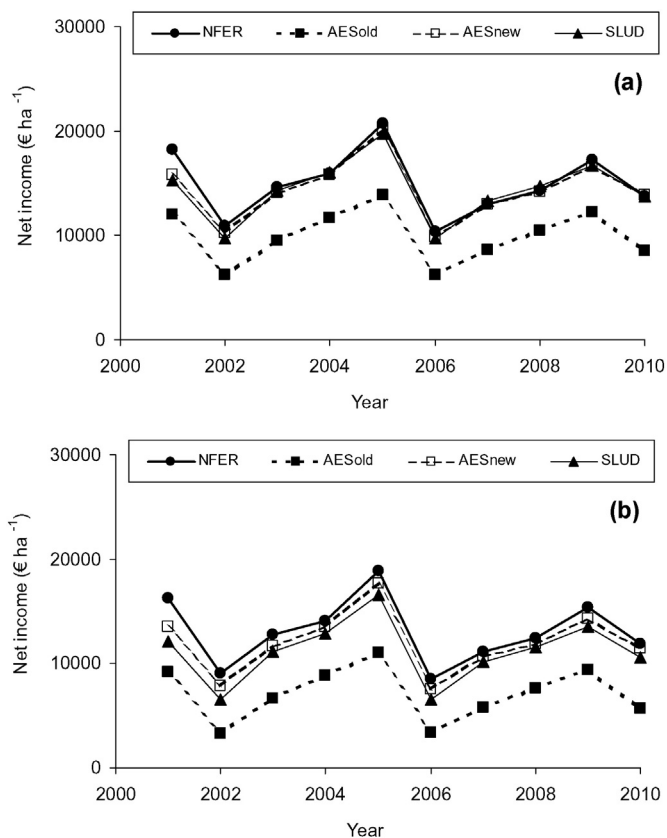


Fig. 5. Net income over 10 years of the simulation for (a) small and (b) large farms. Scenarios: NFER, N fertilizer applied at a rate of $200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; AES, agri-environmental schemes; AES_{old}, compost applied at a rate of $15 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$; AES_{new}, compost applied at a rate of $7 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$ and N fertilizer applied at a rate of $150 \text{ kg N ha}^{-1} \text{ yr}^{-1}$; SLUD, sewage sludge applied at a rate of $20 \text{ Mg fresh matter ha}^{-1} \text{ yr}^{-1}$.

maintain N availability at a relatively high level. These good results explain why many smallholders are orientated toward this type of organic input and did not adopt AES_{old}. On the contrary, the economic performance of SLUD for large farms was much lower than that of NFER, which explains why sewage sludge is not used in these farms (Sierra et al., 2015). Besides, at the landscape scale, the adoption of sewage sludge as an organic amendment is limited because of regulatory constraints. Indeed, because of the high density of human settlements in French West Indies, most farms are located within the exclusion boundaries established by the environmental regulations and cannot therefore be involved in the spreading of sewage sludge. In addition, the steep slopes and high acidity of many ferralsols are also constraints that limit the use of sewage sludge in French West Indies (Journal Officiel de la République Française, 1998).

The AES_{new} appeared to fare better than AES_{old} and was better adapted to the expectations of farmers as it enabled improved crop yields and reduced the labour time required for implementation. Compared to the current NFER strategy, and although AES_{new} slightly decreased yields in the initial years, which might limit its adoption by farmers, the environmental and economic impacts were satisfactory: AES_{new} was found to increase C sequestration, reduce N leaching and maintain farmers' incomes in the medium term. Thus the combination of compost and inorganic fertilizer made it possible to reduce inorganic N fertilization rates in the long term, which is consistent with the findings of Hernández et al. (2014) relative to gardening crops in a temperate region.

The investment in inputs under AES_{new} was higher than with the NFER strategy but lower than with AES_{old}. The same result was obtained with respect to labour time requirements. The later might be a barrier to the adoption of AESs by large farms because compost spreaders are not currently available in French West Indies, and labour costs associated to the manual application of organic amendments are relatively high. For example, manual spreading would require 400 h for the application of 15 Mg fresh compost ha⁻¹, as necessary under AES_{old}, for a 4-hectare farm. Indeed, the results obtained in the present study indicated that only smallholder would be able to adopt AESs at present.

AES adoption rates could indeed be improved if the cost of composts was reduced as these are currently quite expensive in the context of Caribbean agriculture. At present there is only one composting platform in French West Indies. Nevertheless, the price of compost could fall in the future because there are several projects for the construction of additional composting platforms in French West Indies and throughout the Caribbean. According to our models, a 30% reduction in the cost of the compost (i.e. 105 € Mg⁻¹) would be sufficient to bring the AES_{new} income to the level of the current NFER scenario in small farms. To obtain the same result for large farms, the cost of compost should be about 15 € Mg⁻¹, which is unrealistic in the actual context of the compost market in French West Indies.

As shown by the analysis of income dynamics, an increase in the subsidies during the first five years might be necessary to offset yield losses during this period under the AES_{new} scenario. This increase in subsidies would be justified by the benefits generated by this AES with respect to the increase in soil organic matter stocks and the reduction of nitrate leaching. As mentioned above, these concerns are key factors to reduce or stop the negative environmental impacts of agriculture in French West Indies. In order to support the transition to organic fertilization, several authors have also demonstrated the importance of institutional and social networks to limit the fixed and transaction costs of adoption (Espinosa-Goded et al., 2013; Mettepenningen et al., 2013; Sotamenou, 2012). The valuation of C sequestration could also be a means of improving the profitability of organic amendment (Aerstens et al., 2013; Antle et al., 2001; Bangsund and Leistriz, 2008). However, our results have shown that this option would be not relevant in French West Indies because C sequestration induced by organic amendments is not large enough in agricultural soils of tropics.

5. Conclusions

In this study we demonstrated that the characteristics of the organic amendments affect drastically the impact of the AESs designed for the French West Indies. Although the compost currently available in the market would be suitable to promote environmental benefits, it has a low level of available N which decreases crop yields and then net income of farmers. We conclude that the new AES, which combines organic and inorganic N inputs, could fulfil its role in ensuring the application of good land use policies because it could promote C sequestration and reduce the risks of nitrate pollution, while maintaining net income in the medium term for smallholder farmers. AES adoption by large farmers would be more difficult, and it seems clear that the increase of the adoption rate needs the implementation of mechanical application of compost in order to reduce labour costs. However, further research is necessary to identify how the fixed costs of adoption can be overcome and to determine the need for incentives during the first years after adoption, as this can be a critical period for the long term success of AESs.

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