Introducing sheep for agroecological weed management on banana plantations in Guadeloupe: A co-design process with farmers

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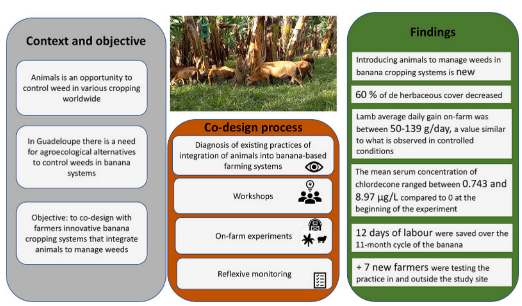
HIGHLIGHTS

- The use of animals is an opportunity to manage weeds in banana plantations
- Our study aimed to co-design innovative systems based on the introduction of sheep in banana cropping systems
- The co-design process included a diagnosis of practices, workshops, on-farm experiments and a monitoring of outcomes
- The process led to positive technical results and first changes in the socio-technical regime
- It is one of the first attempts of introducing grazing animal in productive banana systems

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: In Guadeloupe, the use of a persistent pesticide (chlordecone) contaminated one third of the island's agricultural soils, causing a major environmental crisis. In the aftermath, banana farmers significantly changed their management practices to decrease their pesticide use. With the support of research, farmers have tested and adopted various agroecological practices, such as planting cover crops and using vitroplants and fallow. However, the use of animals to decrease pesticide use on banana plantations has not yet been explored.
OBJECTIVE: This study aimed to co-design agroecological cropping systems that integrate animals as an alternative means to manage weeds.
METHODS: The study was based on co-design workshops involving farmers, advisors and scientists, a survey of local practices of integrating animals within cropping systems, on-farm experiments with four farmers during which a total of 20 four-month-old male lambs were introduced within their cropping systems, and reflexive monitoring two and six months after the end of the experiments.
RESULTS AND CONCLUSIONS: The introduction of sheep into cropping systems was the option deemed the most promising after three co-design workshops. Animals already were integrated into some banana-based farming

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systems in the study area, but this integration mainly consisted of cattle grazing on fallow land. The on-farm experiments highlighted that sheep made it possible to reduce the herbaceous cover on banana plantations by almost 60%. The growth performance of the lambs allowed by the herbaceous cover was within the range observed for this breed when reared on pastures (50–139 g/day). In this experiment, the lambs were not reared for meat, since the animals were, unsurprisingly, contaminated by chlordecone. The farmers appreciated that the practice enabled them to eliminate a labor-intensive activity (removing by hand the vines around the banana pseudo-stem) and radically reduce brush cutting. Piloted by a technical institution providing farmers technical support, initial changes in the broader socio-technical regime were observed.

SIGNIFICANCE: This study highlights a co-design process of agroecological cropping systems involving agronomists, animal scientists, and farmers that led to an innovative, animal-based method of managing weeds within banana cropping systems with positive preliminary adoption outcomes as new farmers start using the practice. Inspired by similar efforts in vineyards, cereal and oil palm plantations, it is one of the first attempts to introduce sheep into banana cropping systems. The challenge is now to support this adoption at the territorial scale through possible cooperation between breeders and farmers, the training of farmers, and finding a means to ensure the safety of sheep.

1. Introduction

Integrated crop-livestock systems produce nearly half of the world's food (Herrero et al., 2010). Many studies have described the services provided by crop-livestock integration at the crop, farm, and landscape scale, including energy provision, soil fertility, valorization of crop sub-products, and resilience and flexibility to cope with economic and climate shocks (Martin et al., 2016; Moraine et al., 2016; Ryschawy et al., 2012; Sempore et al., 2016).

In various cropping systems around the world, studies have focused specifically on the role of animals in reducing pesticide use in cropping systems. Kathiresan (2007) highlighted the positive effect of animals (poultry, fish) on weed control in lowland transplanted rice. Lenssen et al. (2013) analyzed on-station the effect of sheep grazing during fallow periods and found that it had limited impact on subsequent wheat yield and quality, indicating that it could be a suitable practice for weed and residue management in wheat–fallow systems. McKenzie et al. (2016) compared on-station the effect of sheep grazing and mowing for cover crop termination and found that grazing and mowing act as similar ecological filters of both weed and carabid beetle communities. Schuster et al. (2016) assessed on-station the effect of different grazing intensities of a winter cover crop by steer and concluded that decreasing the grazing intensity reduced the number of weed species, the density of emerged weed seedlings, and the weed seed bank density. Tohiran et al. (2019) analyzed the effect of cattle grazing on oil palm plantations and showed that it allowed cover to be maintained at an acceptable height for harvesters to access oil palms. This was an indication that the practice could be an interesting means for farmers to reduce their use of chemical herbicides and align with sustainable palm oil certification policy. In vineyards of New Zealand, Niles et al. (2018) found that seasonal integration of sheep during vine dormancy is common, while integration during the growing season is rare. They also found that farmers perceived benefits in terms of reduced mowing and herbicide use. All these studies highlight the benefits of animals for weed management for diverse crops. However, Pissonnier et al. (2019) simulated the economic performances of a virtual scenario introducing sheep into apple orchards that pointed to a potential economic risk for the main crop. In a review of existing studies on pasturing chickens in orchards, Bosshardt et al. (2022) also highlighted various gaps in knowledge about crop-livestock interactions, such as direct physical impacts of chickens by pecking and scratching or soiling, and indirect impacts on pest regulation, and noted that very few studies had been specifically dedicated to chicken-pastured orchards. They also highlighted the complementarity of farmers' knowledge of the complex interactions that exist in chicken-pastured orchards and scientists' knowledge of underlying processes. Yet despite the growing interest in the use of animals for weed management in cropping systems, farmers are not routinely involved in the design of alternative practices.

The co-design of integrated crop-livestock systems involves diverse stakeholders who work together to develop innovative integration modalities (Sempore et al., 2016; Pissonnier et al., 2019). Various methods are used and combined such as workshops, whole-farm modeling, on-station and on-farm experiments to explore collectively incremental or more radical changes. Various authors have highlighted the relevance of these approaches to combine the various sources of knowledge needed for complex and innovative integrated crop-livestock systems (Ryschawy et al., 2017).

In Guadeloupe, banana is the leading export crop. Farmers used to rely heavily on synthetic inputs to intensify their production, which was subsidized by public policies. Over the past two decades, the banana sector in Guadeloupe has engaged in a transition toward more sustainable cropping systems based on agroecological principles of diversification, recycling, and efficient use of nutrients (Risède et al., 2018, Tarsiguel et al., 2023). This transition was strongly backed by civil society following a major environmental crisis caused by the widespread use of chlordecone that ultimately contaminated one third of the island's agricultural soils and impacted human health (Costet et al., 2015). This pesticide was used in Guadeloupe until 1992 to control the *Cosmopolites sordidus* weevil in banana systems (Lesueur et al., 2016). Today, practices such as the use of fallow and vitroplants, which are plants produced in a laboratory and used to sanitized crops, have helped to control banana parasitism involving weevils and the nematode *Radopholus similis*. The maintenance of sown or spontaneous plant cover under banana plantations also has provided various services, such as the control of erosion, improved soil fertility and weed control. These practices have made it possible to drastically reduce the amount of insecticides, nematicides and herbicides used in these cropping systems. Between 2006 and 2015, the use of nematicides and insecticides was reduced by nearly 90%, and herbicides by almost 50% (Risède et al., 2018). Mechanical weed control also has helped to reduce herbicide use. However, brush clearing is expensive, increasing weeding costs (labor and fuel) nearly fivefold, and does not completely eliminate the use of herbicides. Although the importance of crop-livestock farming systems in Guadeloupe has been demonstrated by several studies (Stark et al., 2016; Fanchone et al., 2020), few have assessed whether animals could play a role in managing weeds and reducing the use of herbicides in cropping systems, particularly banana systems where brush cutting and herbicide use are widely practiced. However, in the island's banana production area, using animals to manage weeds presents both challenges and constraints given that the animals themselves can become contaminated by chlordecone while grazing (Fourcot, 2020).

In the present study, we aimed to co-design with farmers innovative banana cropping systems based on agroecological principles that integrate animals as an alternative to the use of herbicides and brush clearing for weed management in zones contaminated by a persistent pesticide.

This study was conducted in the banana belt of Guadeloupe. The co-design process was conducted as part of a research project funded by the

French Ministry of the Overseas aiming to decrease pesticide use in cropping systems. In a four-step co-design approach, we combined workshops, surveys with farmers, on-farm experiments, and monitoring the first outcomes of the process.

We present below this co-design process and discuss the lessons learned for the design of agroecological systems.

2. Conceptual framework

Co-design approaches in agronomy aim to support farmers in the design of innovative practices at the crop, farm, and territory scale, including the design of innovative decision support systems. They are conducted by diverse stakeholders engaged in a participatory process. Various approaches are used that generally consist of sequential steps, such as in the Describe, Explain, Explore and Design approach (Descheemaeker et al., 2019), the RIO approach (Elzen and Bos, 2019), and the step-by step design approach (Meynard et al., 2023). In co-design processes, diagnosis is a key step to identify the needs of actors, existing practices, and particularly existing innovative practices. It is generally conducted at the beginning of the co-design process. Another step consists of design workshops, where groups of actors explore and build disruptive solutions to reach ambitious goals (Jeuffroy et al., 2022). Co-design workshops are generally conducted after the initial diagnosis of a problem, but also at the beginning of a design process to identify collectively the design target and the subsequent steps of the research. On-farm experiments are common in these approaches (Meynard et al., 2023), they generally aim to test with farmers the most promising options identified during the co-design process (Osorio-García et al., 2020). They make it possible to consider farmers' constraints when implementing the innovative practices (Descheemaeker et al., 2019). While the assessment of the practice tested is common to identify whether the process met its initial objectives in order to start a new design loop addressing new issues, the assessment of the co-design processes is less common, yet it can both trigger a new design loop and feed 'anchoring activities' aiming to stimulate uptake of the novel designs in the broader socio-technical regime (Elzen and Bos, 2019).

3. Materials and methods

3.1. Study site

Guadeloupe's tropical climate is characterized by two main seasons: the dry season (January to April) and the rainy season (July to October). They are separated by two transition periods (Météo France 2022). Temperatures remain stable and mild throughout the year, ranging from 20 to 29 °C on average depending on the altitude.

In the banana belt, the relief, which is perpendicular to the winds coming from the East, regulates the rainfall regime, which ranges from 2000 mm per year to 4000 mm per year.

The study area is located in the districts of Capesterre-Belle-Eau (16.050°N, 61.600°W) and Goyave (16.1333°N, 61.5667°W), which lie within the main banana production belt of Guadeloupe (Fig. 1). Although the use of chlordecone has been banned since 1992, many banana plots have been permanently contaminated by the chemical. Some plots were tested for chlordecone during the ChlEauTerre program in 2017, which revealed the extent to which the soil has been contaminated with this molecule. Four levels of contamination were identified, but many plots have not yet been tested despite the very high risk of contamination due to the presence of bananas during the years the pesticide was used.

Banana does not contain chlordecone. However, the presence of this molecule in the soil limits the cultivation of tubers and some vegetables, as well as livestock farming (Cabidoche and Lesueur, 2011). Animals in

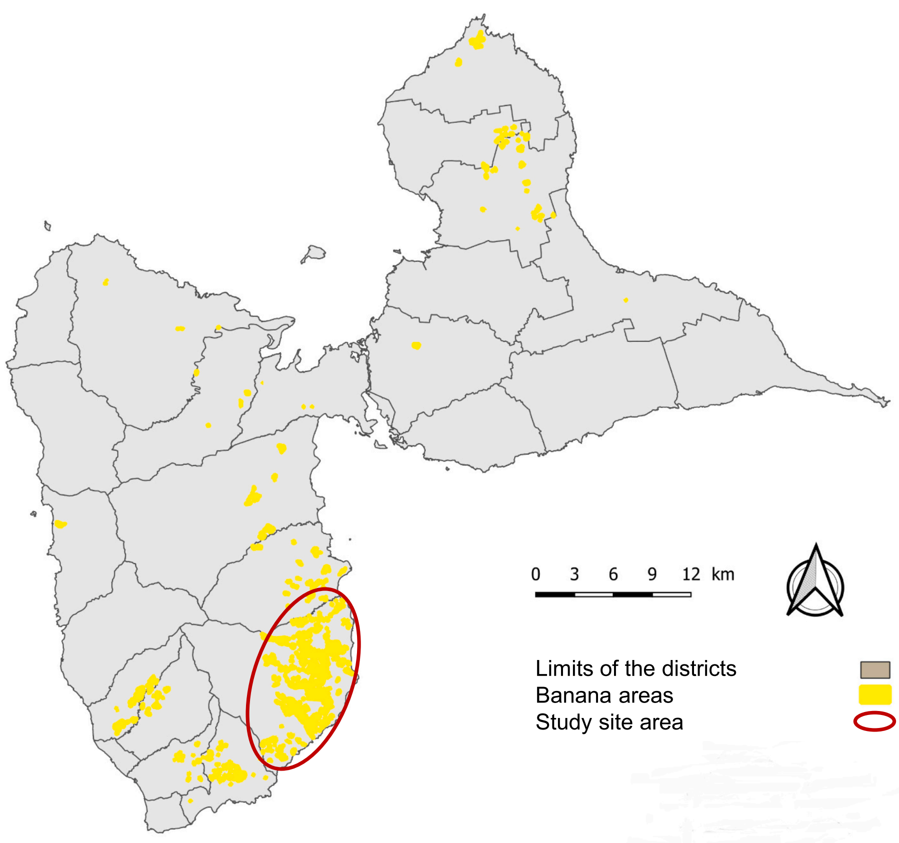

Fig. 1. Location of the study area

this area are contaminated while grazing or drinking contaminated water. Chlordecone is then found in the animals' meat, fat, organs, and products (milk, egg) (Fourcot, 2020). The presence of chlordecone does not present a risk for the health of animals but rather for humans consuming contaminated animal products (Costet et al., 2015). The presence of chlordecone in the carcasses of animals produced in the area is systematically checked at the slaughterhouse and destroyed when the maximum residual limit is exceeded. Animals can be decontaminated, but this involves additional costs for farmers who need to find non-contaminated fodder and water (Fourcot, 2020). Consequently, livestock have progressively disappeared from the area. Three crops (banana (830 ha), sugarcane (350 ha), and plantain banana (40 ha) a category of banana that is generally cooked) and fallow land (460 ha) cover >90% of the site's declared usable agricultural area.

3.2. *The co-design framework*

Our co-design process was based on four complementary steps:

1. Diagnosis of existing livestock integration in banana-based systems
2. Design workshops based on three meetings to identify animal-based options to decrease the use of pesticides in banana cropping systems
3. On-farm experiments of the most promising option to control weeds using animals
4. Reflexive monitoring of the first outcomes of the co-design process.

3.2.1. *Diagnosis of existing practices*

We used individual semi-structured interviews of 17 banana farmers selected by non-random sampling (each banana farmer interviewed was asked whether they could identify a banana farmer rearing livestock) due to the quasi absence of animals in the study area. The aim was to describe the modalities of integration of livestock systems into banana-based systems. The data collected during the surveys included the farm's total surface area, cropping pattern, banana management practices, type and number of animals on the farm, and the feed and manure management of animals. We also collected data on the biomass flows (manure, fodder, other) between crop and livestock systems at the farm and landscape scales.

For each farm, we drew a biomass flow map representing the inflows and outflows of biomass between the crop and livestock systems (Andrieu et al., 2019). We then categorized farming systems according to the function of animals (weed management, fertilization management, other) in the cropping systems. This categorization did not consider potential differences in the amount of biomass exchanged between crop and livestock systems.

3.2.2. *Design workshops*

In our study, the design workshops were based on three meetings. The first workshop was conducted at the very beginning of the project in December 2020 to identify the perceived advantages and limitations of introducing animals to improve the sustainability of banana cropping systems, and to identify possible new ways of involving animals. Although it was an in-person workshop, the number of participants was limited due to the Covid 19 restrictions in force at the time. The participants were three banana farmers from the agronomists' network that were invited to participate due to their previous experience in livestock production (small ruminants or poultry), three agronomists involved in the research program promoting decreased pesticide use, one animal scientist involved for his work on chlordecone contamination, and one representative of the Chamber of Agriculture. The three-hour workshop was facilitated by two of the agronomists. After presenting the overall aim of the project and its articulation with transformations that already had occurred in the banana sector (introduction of cover crops and fallow areas), we asked the participants to identify the potential advantages and limits of animals for banana cropping systems. The questions included: "how can animals help to sustainably improve the management of banana cropping systems?" "what are the constraints (technical, organizational, other) to rearing animals in banana-based production systems?". In a second session of the workshop aiming to come up with a list of banana-livestock integration options, we asked the participants to propose how animals could be integrated into cropping systems in light of the advantages and limits identified: "what are your propositions on how animals could be integrated into banana-based farming systems?". We used paper boards and stickers distributed to participants to list and organize the ideas.

A second workshop was organized in June 2021 that aimed to collectively select the most promising option to test among the ones identified in the first workshop. In this workshop, we reviewed the results of the diagnosis and each of the pre-identified options, considering the implications for the farmers who would test them (e.g., technical skills, cost), the existing scientific knowledge (e.g., on animal feed requirements and dietary preferences, chlordecone risks) for various possible types of animals (cattle, goats, cheeps, chickens). There were eight participants: two banana farmers, one adviser from the livestock technical institute, the four scientists present at the first workshop, and the representative of the Chamber of Agriculture.

A third workshop was organized in October 2021 to reach a collective agreement on the experimental design that involved three farmers, three agronomists, one animal scientist, and three advisors from the *Institut Technique Tropical* (IT2), the institution providing technical advice to banana farmers in Guadeloupe. During this workshop a common protocol was proposed by scientists and discussed with farmers and advisors defining what would be the specific role and contribution of each actor during the experiment.

3.2.3. *On-farm experiments*

3.2.3.1. Experimental design. Four farmers (A, B, C, D) volunteered to include animals in their banana cropping systems and to implement the associated management practices required for animal care during a six-month period, from December 2021 to June 2022. Two of these famers had participated in the previous design workshops, the two additional farmers were selected by IT2 from their network for their willingness to test this alternative and because they had soils contaminated by chlordecone. This was a key criterion as a minority of soils are not contaminated, and farms without contaminated soils would not be representative of those facing this major constraint. Farmers agreed to manage animals according to the experimental design discussed in the third workshop.

The soils on the four farms were andosol (IUSS Working Group WRB, 2022). The planting density of bananas varied from 1400 and 1600 plants/ha, and bananas were planted in single rows in two farms (A and B), and in double rows with large inter-rows in the two other farms (C and D). Banana are generally planted in double rows in mechanized plots. Conversely, plots that cannot be mechanized (on steep slope for example) are planted in single rows.

All measurements and observations on animals were carried out in accordance with the current law on animal experimentation and ethics, and were approved by the French Ministry of Agriculture (authorization number: HC-69-2014-1) after evaluation by the Animal Care and Use Committee of French West Indies and Guyana (*Comité d'Ethique en Matière d'Expérimentation Animale des Antilles et de la Guyane*, C2EA-69). A total of 20 weaned male Martinik lambs (21.25 ± 4.9 kg live weight (LW); 141 ± 6 days of age) were randomly divided into four experimental groups corresponding to the four selected farms ($n = 5$ lambs/farm). All of the animals were reared at the INRAE PTEA experimental farm before the start of the experiment and were contamination-free. More details on the experimental design that was collectively defined is presented in the results.

3.2.3.2. Data collected. We monitored four variables from December 2021 to June 2022 that would help describe the ability of animals to control weeds in banana cropping systems and the associated effects on animal weight and chlordecone contamination (Table 1):

- Height of herbaceous cover;
- Floristic composition of herbaceous cover;
- Animal weight gain;
- Animal chlordecone contamination.

3.2.3.3. Data analysis. For the various variables, we carried out an analysis of variance on ExcelStat ® to determine significant differences between the values measured at the beginning and end of the experiments for the various farms.

3.2.4. Reflexive monitoring of the first outcomes of the co-design process

We monitored the participating farmers two and six months after the end of the experiments to identify:

- their perception of the benefits and limits of the practice they tested;
- whether the practice was still used on the farm and changes needed for up-scale;
- changes farmers implemented to the initial practice;
- reasons for abandoning the practice.

We also noted the types of changes in the socio-technical landscape, in particular the new actors (farmers or institutions) developing the practice that may have appeared.

In parallel, we conducted activities aiming to support the uptake of the practice such as its presentation in the local media and YouTube, and its presentation to actors of the livestock sector.

4. Results

4.1. Five types of livestock integration into banana-based systems

Livestock in the area consisted mostly of pigs and cattle. Five main types of farming systems were categorized (Fig. 2).

Type 1, “Banana system with outgoing banana sorting rejects”, includes eight farms ranging in size from 6.5 to 85 ha. The main flow of biomass between crop and livestock systems observed in this type corresponds to sorting rejects from banana production (banana fruits that present defaults and cannot be exported or used in the local market) which are given or sold to breeders across Guadeloupe. The farms generate between 250 and 3000 kg of sorting rejects each week. A second biomass flow, practiced on two farms, consists of using banana rejects (200 kg per week) to fertilize fallow land. One farmer directly spreads the rejects on the fallow land while the other crushes the rejects before spreading them.

Type 2, “Banana system with breeding”, is a production system that includes banana cropping on 5 to 14 ha and pig or goat breeding. This type includes four farms. The main biomass flows correspond to feeding sorting rejects to pigs and goats (1000 to 4000 kg per week) and the use of pig slurry (from 20 tons to 120 tons.ha-1 per year) or compost to fertilize fallow land (80 tons .ha-1 per year). An outflow, corresponding to the donation of slurry to other banana farmers at the rate of 50 to 150 tons of slurry twice a year, was observed on two of the four farms. In one additional case, there was an exchange of incoming slurry for sorting rejects intended for pig feed because the farm’s slurry production was insufficient.

Type 3, “Banana system with inputs of organic matter through cooperation with breeders”, consists of a single farm with 200 ha of banana. The banana farmer recovers pig manure from a pig farmer at the rate of 10,000 tons once or twice a year and uses it to fertilize his fallow land. He also collects chicken droppings from a poultry farmer at the rate of about 230 tons per year which he uses to fertilize banana plots and fallow land. This farmer sells his sorting rejects to breeders all over Guadeloupe at the rate of 19 tons per week.

Type 4, “Banana system with use of external oxen for grass cover management and fallow fertilization”, includes two farms. In this system, cattle outside the farm are used to manage grass cover and fertilize fallow land. One farm grows 14 ha of banana, the other 3 ha of bananas. The cattle belong to relatives (family members or employees) who bring their cattle to the fallow plots (1 to 2 cattle per ha stay on a plot for about 15 days or 5 to 7 cattle for 3 months). The sorting rejects are again sold (approximately 3000 kg per week) or given to breeders when the volumes are smaller (600 kg to 1000 kg per week).

Type 5, “Banana system with integrated cattle breeding”, includes cattle which are used for the destruction of banana plantations and then the management of grass cover and the fertilization of fallow land. This type includes two farms, both of which cultivate 5 ha of bananas. Two to five cattle per ha are left on the plots for both the destruction of plantations and for the management of grass cover and fertilization on these plots. In both cases, the farmers have other livestock systems. On one farm, there are laying hens whose droppings are collected once a week to fertilize market gardening plots; on the other, there are pigs consuming 100 kg per week of sorting rejects. The second farmer also collects 10,000 kg of cattle manure per year and 20,000 kg.ha^{-1} per year of sugarcane bagasse from a distillery for the fertilization of banana plots. Sorting rejects are either given away at a rate of 100 to 120 kg per week or sold to pig and goat breeders at a price of 20 euros for 200 kg per week.

This diagnosis of existing practices highlights that in the banana-based systems, the crop and livestock are integrated at the farm and territorial scale. The purpose of this integration is mostly to fertilize the crop. However, two of the five types of farming systems (types 4 and 5) also use animals to control weeds, but only on fallow land. In other words, the use of animals for weed management is a local practice; however, animals are never put on productive plots to avoid damage to the banana plants. Introducing animals on banana plantations is consequently a new practice but one anchored in existing local practices.

4.2. The co-designed options

During the first workshop, participants recognized the positive role that animals could play in banana cropping systems. However, they listed various constraints to their introduction based on their previous experience (Table 2).

They also listed alternative ways to strengthen the role of animals within banana cropping systems (Table 3). These options corresponded to distinct functions that animals could play in cropping systems:

Table 1
: Description of method and frequency of measurements for indicators followed in the experiments.

Variable	Method	Frequency
Herbaceous cover		
Height	Herbaceous cover measurement using yield squares at entry and exit of animals in a paddock	A typical week during the third month of the experiment
Botanical composition	Botanical survey (quadrat point transect as described by Daget and Poissonet (1971))	Beginning and end of experiment
Animals		
Weight gain	Animal weighing	Every month
Chlordecone contamination	Collection of blood samples for serum chlordeconemia conducted by the Institut Pasteur with a proven method used routinely in the laboratory according to Saint-Hilaire et al. (2019).	Every 2 months

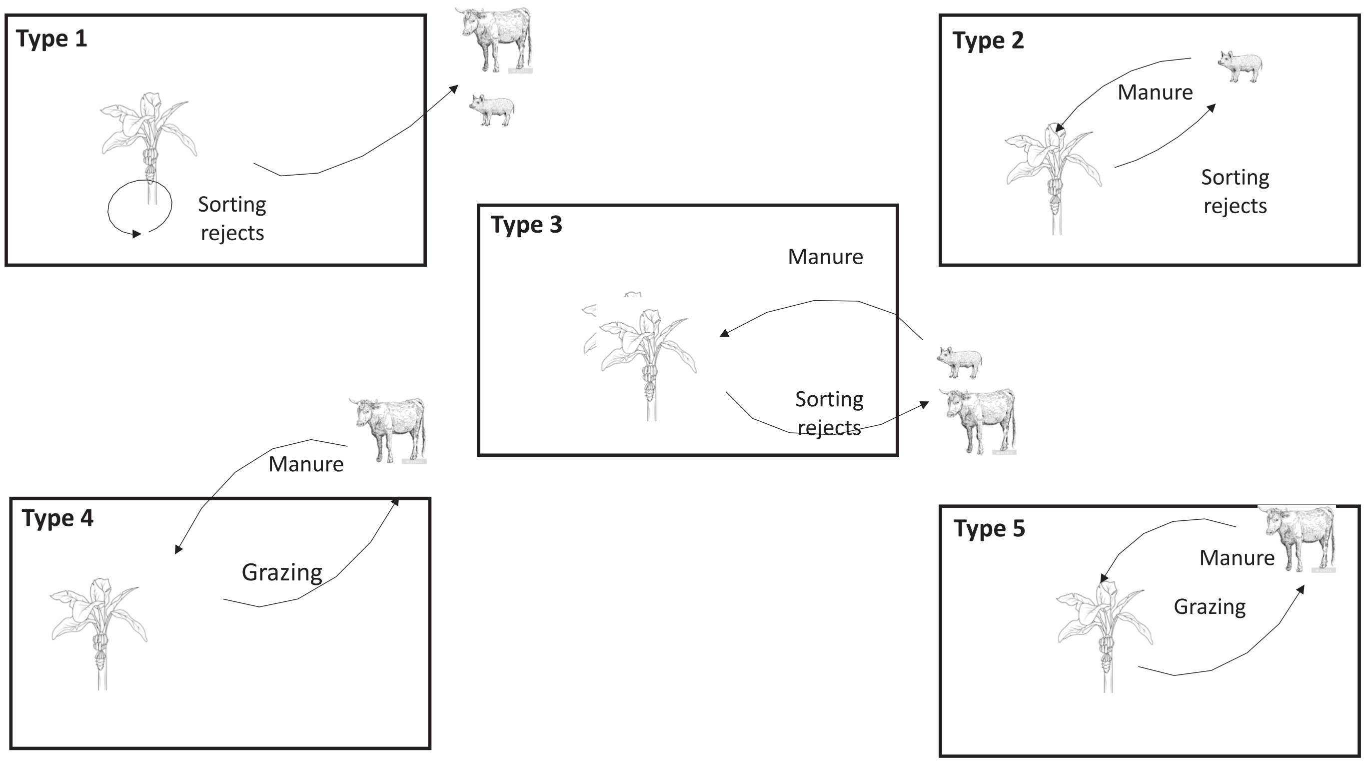

Fig. 2. The five farm types identified according to the banana-livestock integration

Table 2
Advantages and limits of integrating animal within banana cropping systems determined after the first workshop.

Advantages	Limits
Animals can help manage bio-aggressors (e.g., geese eat snails, hens eat weevils)	There are various predators (dogs, mongoose)
Thanks to the manure and urine produced by animals, their presence can decrease the need to purchase organic matter	There is a need to fence plots to protect animals from predators
Animals can be fed bananas sorted for discarding	Trampling by cattle may cause soil compaction
The use of cattle to destroy fallow land is subsidized by the Agro-Environmental and Climate Measures (AECM) proposed by the European Union	Animal theft (mainly goats) is frequent in the area
They are possible agreements with neighbors who own animals and can put them on fallow lands	Being a livestock farmer is a different profession than being a banana farmer
	Additional workforce is needed to manage the animals
	Animals contaminated with chlordecone above a certain concentration cannot be sold
	Significant decontamination time for animals that are sold for food
	There are no breeder/fattener systems

- Soil fertility and valorization of banana crop sub-products in options 1 and 3
- Control of weeds and bio-aggressors in options 2 and 4
- Meat production in options 1 and 4.

During the second workshop, the second option emerged as the one to pursue. The participants considered that the first option required technical skills outside most banana farmers' current repertoire, and was costly due to the need to invest in above-ground infrastructure. They ruled out option 4 for the same cost reason. Although the third option did not require banana famers to acquire new skills, it was not selected because the farmers assumed that it would require organizational innovations at the territorial scale, such as agreements between banana farmers and livestock farmers that would define the amount, frequency and modality of biomass exchanges. The second option, where animals would render a service to the banana crop, was considered the most promising. Based on technical information shared by the animal scientist concerning various animals' dietary preferences, participants selected sheep as the animal to test, considering that they posed less of a risk for the banana crop than goats.

During the third workshop participants defined the experimental design. The animal scientists proposed that on each farm, five animals be placed on 0.5 ha plots composed of a mixture of tropical grasses. This stocking rate is lower than the one used in intensive management of this sheep breed in the tropics, with ranges between 15 and 30 weaned animals per ha (Mahieu et al., 1997). It was proposed to limit the risk of the sheep grazing on the banana plants if there was a grass shortage. The animal scientists also suggested following a 4-plot rotation system delimited by electric fences, with a length of grazing estimated at seven days per plot (i.e., a 21-day interval of grass regrowth). This was intended to limit the risk of gastro-intestinal parasitism for lambs and was based on experimental results (Fig. 3) (Mahieu, 2013). Electric fences were suggested by a farmer to limit the risks of dog attacks, which was mentioned as one the main obstacles for livestock introduction in the first workshop. To prevent dog attacks, it also was suggested that the animals be moved every evening to a breeding shelter. Farmers were advised to distribute commercial concentrate at the end of each day (150 g/animal) to balance the animals' diet. During the workshop, farmers again raised the question of the risk of banana consumption by animals. An animal scientist suggested applying a natural repellant based on *Aloe vera* (L.) on the bananas. Despite these technical recommendations, we agreed that the farmers would adjust the protocol based on their own constraints, but they had to record all adjustments made. We also agreed that farmers would decide the rotation and watering of animals within the paddocks. The scientists would provide healthy animals, the electric fences, the commercial concentrate, and the shelter. They also would monitor the variables used to monitor the experiment.

Table 3
The alternative banana-livestock integration options identified determined after the first workshop.

Option	Description	Chlordecone contamination risk	Requires breeding skills
1. Above-ground breeding	Animals managed above ground use fodder produced in part on the farm (pig fattening with banana bunches) and produce manure for fertilization. This scenario is intended mostly for farmers already practicing livestock farming.	−	+
2. Service animal	Animals can help reduce pest pressure or control weeds while fertilizing the soil, but the meat produced is not valorized. This option would apply to farmers who do not wish to develop a livestock farming unit but are interested in the services provided by animals.	+	+/−
3. Territorial cooperation	Banana farmers sell their sorting rejects (which can represent up to 10% of production) as well as cover crops with fodder value to breeders who in return sell animal waste. Integration thought out at the territorial level does not require the transformation of professions but rather better cooperation. Nevertheless, it is necessary to ensure that the cover plants are not contaminated by chlordecone.	+/−	−
4. Forced decontamination	This option is complementary to option 2 but requires an above-ground rearing phase as for option 1 but more reduced in time and space. The recommended duration for decontamination is 3 months for goats and 215 days for cattle.	−	+

4.3. On-farm experiments

We found an average decrease of 60% of the herbaceous cover between the entry and exit of animals (Fig. 4), the difference between values of biomass at entry and exit being significant at $p < 0.01$. Regarding the cover composition, we found a decrease of grasses such as *Panicum* maximum, *Brachiaria Mutica*, and *Paspalum conjugatom*. The most impressive decrease was a decrease in *Commelina elegans*, a vine that grows around the banana pseudo-stem.

The average daily gain (ADG) ranged between 50.1 and 139.1 g/day during the six-month experiment, in accordance with the production potential measured for this sheep breed in controlled studies (Marie-Magdeleine et al., 2010) (Table 4). The highest ADGs were observed on farms B and C and the lowest on farm D (respectively, 139.1 ± 1.17, 126 ± 3.94 and 50.1 ± 4.87 g/day). No difference was observed between farms B and C. No chlordecone was detected in the serum of the animals at the beginning of the experiment (data not shown). After six months at pasture on the four farms, the mean serum concentration of chlordecone ranged between 0.743 and 8.97 μg/L. The highest serum concentration of chlordecone was observed on farm A (8.97 ± 2.28 μg/L) and the lowest on farm D (0.743 ± 0.215 μg/L); there was no statistical difference between farms B and C (1.56 ± 0.221 and 3.97 ± 1.28, respectively). No difference was observed between farms A and C. A high variability between individual animals was observed on all of the farms.

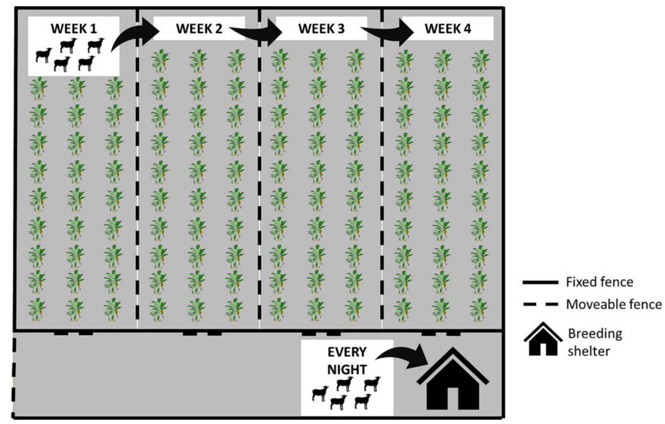

Fig. 3. On-farm experiment (0.5 ha, 6 months) based on 4-plot rotation system (5 lambs) repeated in 4 farms of 4–11 ha in size.

4.4. Reflexive monitoring of the design process

4.4.1. Farmers' perception of the practice

The farmers had all an overall positive perception of the practice. They particularly appreciated the consumption of the vines around the pseudo-stem. This eliminates a labor-intensive activity, trimming (representing 4.5 days of labor over the entire banana crop cycle, Fig. 5), which consists of removing by hand the vines growing along the pseudo-stem: "what appeals to me the most about this is that the animal has removed two tasks, brush cutting and trimming". This perception confirms the botanical measurements presented in Fig. 4. One of the workers in charge of trimming and present during the survey indicated "the sheep gave us valuable support". Another farmer observed that the sheep consume the herbaceous biomass on the rows and the inter-rows but leave refusals (the less palatable part of the grass). Three of the four farmers deemed that their banana yields were not affected by the remaining herbaceous cover, which allowed them to fully eliminate brush cutting (representing 18 days of labor over the entire banana crop cycle). However, one farmer preferred not to risk any banana yield loss (due to competition for water and nutrients between the herbaceous cover and banana plants) and continued to use a brush cutter to eliminate this remaining biomass. Nevertheless, he considered that the presence of the animals reduced the volume to be cleared out, particularly on sloping plots, thereby lightening the burden of this arduous task. The farmers mentioned that animals did not eat the banana regrowth or only the first leaf when the duration of grazing on the same paddock was longer than the time recommended in the experimental design. The consumption of the first leaf was then considered by the farmers as a signal that it was time to move the animals to the next paddock.

Farmers mentioned new tasks, such as the rotation of the animals within the paddocks (representing a total of 6 days over the whole crop cycle) and clearing under fences (4.5 days in the whole banana crop cycle). While the rotation of the animals within the paddocks, which took 20 to 30 min per day, was deemed to be a relatively easy task, it did require someone to be present on the farm every day. The main

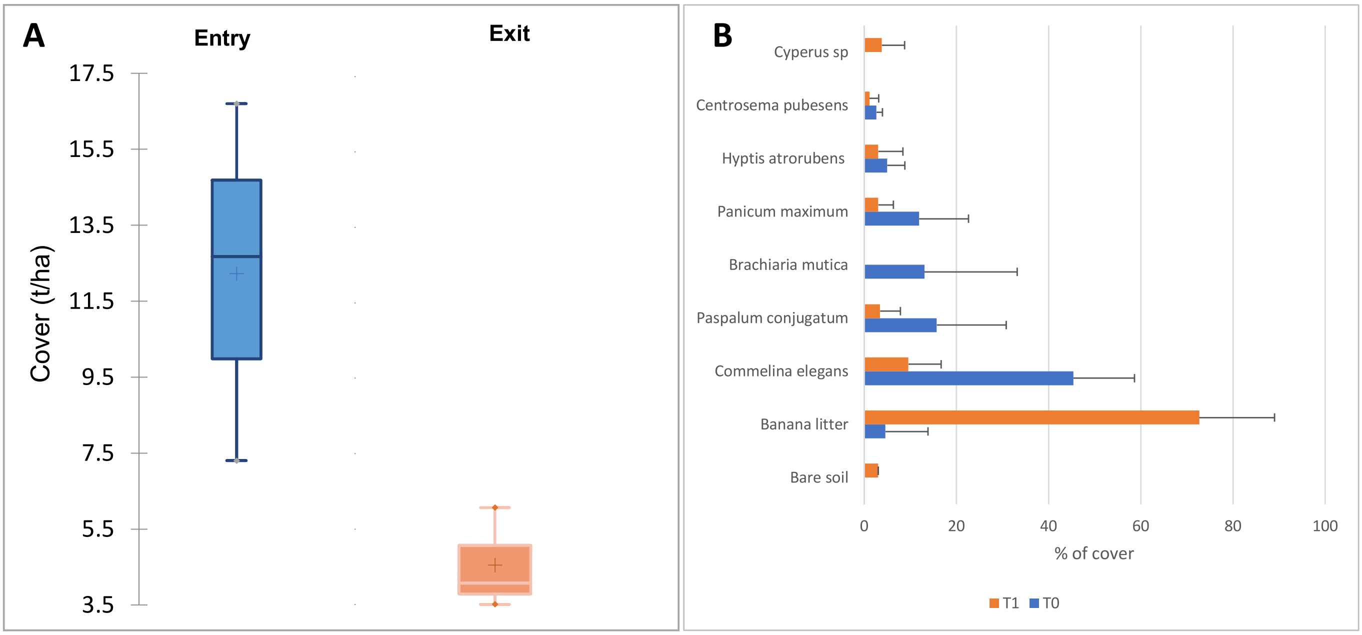

Fig. 4. Evolution of herbaceous cover under a banana crop for the four farms (A) box plot representing the height of cover after entry and exit of animals in a paddock with bars highlighting min and max values and (B) cover composition between the beginning (T0) and end (T1) of the experiment with bars indicating the positive value of standard-errors.

Table 4
Average daily gain and serum concentration of chlordecone during the experiment.

Farms	ADG[1] (g/day)	Serum chlordecone[2] (μg/L)
A	103.1 ± 7.0[a]	8.97 ± 2.28[a]
B	139.1 ± 1.17[b]	1.56 ± 0.221[b]
C	126 ± 3.94[b]	3.97 ± 1.28[ab]
D	50.1 ± 4.87[c]	0.743 ± 0.215[b]

Means with different superscript within a row are significantly different ($P < 0.05$).
[1] ADG, Average Daily Gain, Means ± standard error of the mean.
[2] Serum chlordecone, Means ± standard error of the mean, measured at the end of the experiment, after a 6-months pasture period

constraint was the management of the electric fence, particularly among inexperienced farmers. Discussions with farmers show that these new tasks were perceived differently depending on the farmer's experience with keeping animals on their farms. For the two farmers who already had animals, these new tasks were perceived as less painful than weeding work with brush cutters. "With the brush cutter, you have 10 kg on your back during 7 hours, weeding never ends since when you finish some plots, you have grass regrowth in other plots". However, another farmer without experience in livestock farming mentioned "it is constraining to go back to the farm on the weekend".

4.4.2. The first socio-technical changes

The monitoring carried out six months after the end of the experiment highlighted various socio-technical changes: changes in the practice by implementing farmers and the start of a scaling process led by the

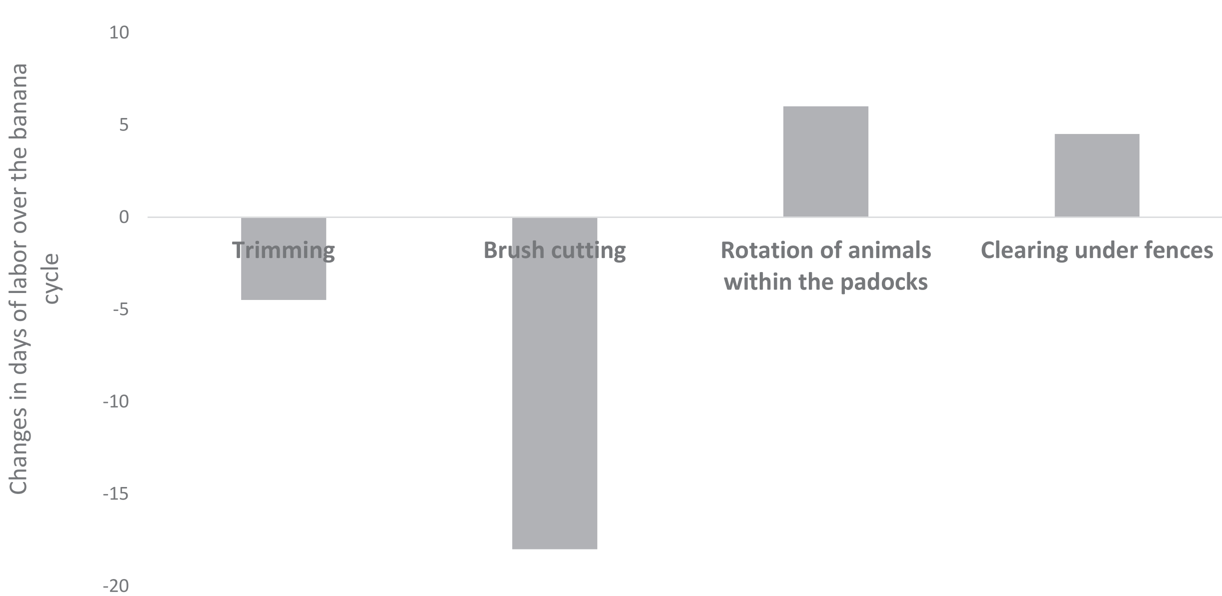

Fig. 5. Average changes in labor-days after the introduction of sheep into banana cropping systems

institution providing technical advice to banana farmers (Fig. 6).

Two of the four farmers were still using the practice with adaptations; they are the farmers who already had livestock on their farms. The first doubled the number of sheep as well as the grazing area under bananas. He thus went from an experimental plot of 0.5 ha to 1 ha, but kept the same livestock load (218.5 kg of LW/ha). He adapted the fence system to promote animal mobility by combining mobile and fixed fences. The farmer mentioned an interest in increasing the number of sheep, and noted the need to increase the value of the POSEI to incentive the practice. POSEI is a scheme that supports the European Union's outermost regions which face specific challenges due to remoteness, insularity, small size, difficult topography or climate, and is key to maintaining banana production in Guadeloupe. The second farmer kept the animals on the banana plots, but restricted their mobility by leading them to the plots and attaching them to stakes. The farmer plans to increase the number of animals, but at the time of the monitoring visits the number had not changed. A third farmer remains interested in the practice and kept the animals, but he does not know how to manage the fence. This farmer was the one with the least experience in livestock farming. The animals were moved out of the banana plots. One of the farmers lost his herd after the experiment due to a dog attack: "when I arrived in the morning to the farm, the dog was still there, but the animals were dead". This illustrates the risk pointed out very early on by the farmers during the co-design workshop.

Three new banana farmers in the area have spontaneously replicated the practice. They all knew at least one of the farmers participating in the experiment and trusted their positive feedback on the practice. They all had experience in livestock farming and decided to experiment with the introduction of animals into banana plots using their own resources.

IT2 has included the provision of technical support to farmers interested in introducing sheep in their banana cropping systems in the institute's strategic plan. In addition, the institute started promoting this practice in late 2022 with four new farmers from another neighboring department (Martinique). They also submitted a proposal for funding that aims at introducing animal in other cropping systems on Guadeloupe.

5. Discussion

5.1. Sheep grazing is a relevant alternative for weed management in banana cropping systems

This study made it possible to co-design with field actors cropping systems integrating animals. Compared to existing practices used in banana systems in Guadeloupe and elsewhere to control weeds with herbicides and brush cutters, this practice was innovative. It also was innovative in that it integrated animals directly onto productive plots rather than to control weeds on fallow land as it is currently done by farmers from types 4 and 5 of our typology.

In line with the work of other authors, this co-design process shows that introducing animals into cropping systems can help control weeds with low risks for banana regrowth when farmers properly control the duration of grazing (Lenssen et al., 2013; McKenzie et al., 2016; Schuster et al. 2016; Tohiran et al., 2019). The range of animal performances (ADG) were within those observed for this breed raised on pastures in the same agro-pedoclimatic conditions (Archimède et al., 2008; Marie-Magdeleine et al., 2009). In contrast, as expected after being pastured for six months on the banana plantations, all of the animals were contaminated by chlordecone (Jurjanz et al., 2014). Interestingly, a high variability between animals was observed both within and between the four farms, pointed to the need for supplemental work to understand in detail how this variability is determined.

Further studies are also needed to quantify greenhouse gas emissions linked to animal introduction versus those linked to fuel and brush cutter importation and use (Fanchone et al., 2022). Lastly, research could be done on the optimal carrying capacity on banana plots to limit refusals without increasing the risk of animal parasitism or soil compaction.

Fig. 6. Main changes in the socio-technical regime of banana farmers.

We found that the management of weeds by sheep effectively reduced the hard manual labor involved in brush cutting and trimming. Both the total amount of work and the physical difficulty of the work involved decreased, but the nature of the work changed (weed clearing versus routine work with animals). As demonstrated elsewhere, work, and particularly the physical difficulty of and meaning given to work (Bezner et al., 2022), are key in the adoption of agroecological practices. Christiansen et al. (2023) highlighted that stakeholders engaged in agroecological transitions considered that the human and social dimension are important factors, technical solutions are viewed as secondary. Human and social dimension included capacities, value of work but also farmer well-being. Consequently, this practice will not suit all farmer profiles, those most likely to adopt it seem to be those who already have experience working with livestock.

5.2. Drivers and lock-in for the large-scale adoption of the practice

The current socio-technical regime in Guadeloupe was favorable to the first signals of adoption of the practice, particularly the pressure from civil society pushing for the transition of agricultural systems, the institutional changes (such as policy incentives and the structuration of the banana sector) that already had taken place to support the adoption of cover crops and vitroplants in banana systems (Risède et al., 2018), and the new regional agroecology plan that is encouraging the emergence of this type of practice (Region Guadeloupe, 2020). The increasing cost of synthetic inputs, which have become expensive, as well as the brush cutter, which also is costly and involves grueling labor, may explain these positive first signals. Additional changes in the socio-technical regime are needed. Stray dogs could be a major constraint to the development of the practice. The risk posed by dogs was highlighted during the first workshop, one of the participating farmers lost his livestock to a dog attack, and public measures to control stray dogs are limited. Additionally, the risk of contaminated lamb being introduced in the food chain through illegal markets cannot be excluded, further studies are needed to evaluate to possibilities of decontaminating the animals by farmers (Fourcot, 2020). More control of illegal markets also is needed.

Geels (2011) showed that changes at the level of a niche can also cause changes in the socio-technical landscape to foster innovation. We observed initial changes in the socio-technical regime following the co-design process, such as the inclusion of the practice in the strategic plan of the institution in charge of supporting banana farmers and the first signals of a scaling-up process. As suggested by Elzen and Bos (2019), our activities to stimulate uptake of the practice could be improved to strengthen the networks of actors supporting the identification of actions, particularly actions targeting policy makers.

5.3. Implications for the integration of cropping and livestock systems

The introduction of sheep into banana cropping systems is an example of 'new integrated crop-livestock systems' defined by Garrett et al. (2020). These systems seek to maintain high outputs while reducing external inputs and increasing input efficiency through synergies between crop and livestock systems, thereby maintaining or increasing economic competitiveness. During the first workshop, farmers identified alternative ways to strengthen the role of animals within banana cropping systems. In this process we explored the service animal option and discarded the above-ground breeding, territorial cooperation and forced-decontamination options. For banana farmers without previous experience in livestock farming, the territorial cooperation option could be further explored. Moraine et al. (2016) and Martin et al. (2016) highlighted the soil fertility and biological regulation services as well as the social and economic benefits of developing crop-livestock integration at territorial scales. At the territorial scale, groups of farmers can negotiate land-use allocation patterns and exchange materials such as manure, grain, and straw. Crop-livestock integration for weed management of banana plots at the territorial scale of Guadeloupe is in line with local practices where animals belonging to family members or employees are used to control weed on fallows. Developing territorial cooperation would allow banana farmers to benefit from animal services without radically changing the nature of their jobs, like, for example, landless pastoralists (Muhammad et al., 2019). It would, however, require more formal agreements than those currently existing, where crop and livestock farmers would define the spatial and temporal modalities of interaction and potential share the costs of damages to crops or animals (Martin et al., 2016). For the farmers that gained experience in animal production, the forced-decontamination option appears to be a future avenue to add value to the practice while limiting the risk of supplying contaminated meat on informal markets. Niles et al. (2018) highlighted that in vineyards of New Zealand, farmers mostly integrate sheep during vine dormancy. This seasonal integration can be further explored in banana crops, where animals could be introduced the first six months in new plantations for farmers that fear damage to their crop.

5.4. Lessons learned for the co-design of agroecological practices

The co-design process we implemented shares a lot of similarities with other existing co-design process of agroecological systems based on sequential steps (Descheemaeker et al., 2019; Vall et al., 2016). This process started by a diagnosis of farmers' local practices, various meetings with stakeholders in workshops to identify the target of the co-design and the experimental design, and then testing the most promising options on farms. However, the outcomes of similar co-design processes are not always reported. Duru et al. (2015) distinguish weak agroecology, based on a simple substitution of synthetic inputs by organic inputs, from strong agroecology, based on the redesign of cropping systems to better rely on ecological processes in order to provide ecosystem services. The co-design process led to an ambitious cropping system redesign via animal integration within cropping systems to better optimize the weed regulation service provided by animals. For this type of redesign, new crop management rules are needed to match the animals' forage needs with the plant cycle, and to make the entries and exits of animals into the paddocks consistent with the cropping calendar (plant care, fertilizer supply, harvest). As demonstrated elsewhere in such complex agroecological systems, observation is key (here the consumption of sprouts as an indicator of animal rotation). The exchanges and combinations of the empirical knowledge of farmers (on banana cropping management) and the scientific knowledge of agronomists (on weed management) and animal scientists (on the feeding behavior of sheep) also were key for this redesign (Bosshardt et al., 2022). They were facilitated by the workshops but also by the on-farm experiments that enabled knowledge on a new object to be created. Girard and Navarrete (2005) showed the need for such transdisciplinary approaches and action research. Existing co-design tools at the farm level could have been used to redesign with farmers cropping and livestock systems (Sempore et al., 2016; Pissonnier et al., 2019). They will be relevant to support new loops of co-design where economic benefits or other environmental outputs could be quantified. This co-design process triggered a desire by local actors to explore the opportunities of using animals in other cropping systems on Guadeloupe. Rather than transferring the practice, applying the co-design process may help to define the specific modalities of integration of animals for these crops. Questions that could be explored include: Are there existing local practices of introducing animal on that crop? Which specific animal type will reduce potential risks of damage to the crop and with what animal load? How will these new farmers perceive the practice?.

6. Conclusion

Through a co-design process that included a diagnosis of existing practices integrating animals in banana systems, workshops with farmers, scientists, and advisors, on-farm experiments with four farmers who introduced 20 sheep into their cropping systems, and a reflexive monitoring of the co-design process, we sought to co-design innovative alternatives to the use of pesticides and brush cutters in banana systems. The analysis of existing practices allowed us to identify five types of farming systems with varying interactions between banana systems and livestock systems. None, however, included the introduction of animals to manage weeds on plots. We identified with stakeholders four options to better integrate animals into banana systems. The most promising was the use of sheep to control weeds on productive banana plots. The on-farm experiment conducted with four farmers highlighted that sheep can fully control weeds in plots while posing only minor risks to the banana plants. Unsurprisingly, the sheep were contaminated by chlordecone. While the amount of time needed to control weeds in the cropping systems was reduced, new tasks arose that were required for animal management. However, the physical difficulty of this work was reduced compared to brush clearing, confirming that sheep can be a relevant alternative to control weeds in banana cropping systems. The co-design process supported knowledge exchanges and led to positive signals of adoption of the practice in the banana area of Guadeloupe and in another banana area. Changes are needed in the socio-technical landscape to support such a strong agroecological transformation of banana cropping systems. These changes include more effective controls of stray dogs at the territorial scale, and a policy instrument providing incentives to encourage the adoption of agroecological practices. A decontamination phase to limit the risk of contaminated meat being introduced into the food chain also should be supported. Lastly, further research is needed on new modalities of integrating sheep into banana cropping systems that considers factors such as other livestock loads, work organization, and seasonal and territorial integration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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