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OPEN SCIENCES

FINAL SCIENTIFIC REPORT

"SECURE"

Soil ECological function REstoration to enhance agrosystem services in rainfed rice cropping systems in agroecological transition

SYNTHESIS

Agriculture is at the heart of many international concerns and at the center of social, economic and environmental issues. This is particularly true for countries in sub-Saharan Africa like Madagascar where the majority of the population lives of agriculture, in great poverty. It is therefore urgent and necessary to transform agriculture to improve productivity, sustainability, food security and the standard of living of farmers. One of the paths to success is to ecologically and sustainably intensify this agriculture by increasing the provision of ecosystem services. This involves in particular developing strategies for the sustainable management of natural and renewable resources, whether it be the organic fertilizers available to farmers or soil biodiversity. The other path to success is to build innovative practices with farmers and political support. This involves research projects combining many disciplines with the same objective.

The objective of the SECuRE research project was to improve the fertilization practices of rainfed agriculture, on slopes, in small farms in the highlands of Madagascar, based in particular on a better management of organic fertilizers and soil biodiversity. The intensification of soil ecological functions, provided by soil organisms, indeed offers significant potential for improving agricultural productivity and sustainability, but also for the mitigation of climate change by storing carbon in the soil or for the reduction of soil losses by erosion. This transdisciplinary project therefore aimed to: (i) understand fertilization practices and the level of intensification of small farms, (ii) study the role of certain key soil organisms in relation to the soil and growth of cultivated plants, with rice as a model, (iii) study the potential of assemblages of (organic, mineral, rock-based) fertilizers, (iv) test innovative practices in the field and share them with farmers so that they can guide practices, (v) inform politicians of the potential for ecological intensification of agriculture in Madagascar, and finally (v) disseminate knowledge so that it is known to the greatest number, for a sustainable development of African agriculture.

The project has notably enabled, thanks to a vast survey, an in-depth knowledge of the functioning of family farms in the Highlands of Madagascar. More than 320 farms were surveyed, in two contrasting regions. A great deal of information has been acquired on the farms themselves (size, composition, sources of income, typology of farms), on fertility management practices (practices, materials used, biomass flows) and on economic performance. At the same time, experiments in the laboratory or in the field have made it possible to clarify our knowledge of the role of key soil organisms on soil properties and plant response. In the very infertile, multi-deficient, unresilient soils of the Highlands of Madagascar, our research has clarified the need to strengthen soil biodiversity to intensify the ecological functions it fulfills: recycling of nutrients, decomposition of organic matter, soil structure maintenance and regulation of populations of pathogens and diseases. Our work has shown in particular the role that earthworms can play in the fight against rice blast disease, and the need to choose varieties of cultivated plants capable of "interacting" with soil organisms. Our work has also considerably improved the choice of possibilities in terms of fertilization. The work carried out within the framework of M. Raminoarison's thesis showed the interest of mixing different local fertilizing materials (organic, mineral, rock-based) to fight against multiple soil deficiencies, promote the availability of nutrients for plants and support soil life. Field trials have made it possible to test a set of innovative practices and to compare them with peasant practices in terms of agronomic performance and ecological functioning of soils. All of these innovative practices were shared and discussed with farmers who were able to assess and develop them.

It is still difficult to assess the impacts of such a project. Farmers have always been very present and associated with the project through socio-economic surveys, various workshops on fertilization practices, and reference farms. They have probably realized the possibility of ecologically intensifying their agricultural production for better productivity, greater sustainability and increased income. A survey showed early mechanisms of learning with reference farmers, mainly relying on exchanges of information inside and outside of the networks of reference farms. Malagasy politicians (represented by different Ministries), donors and various NGOs were also informed of these scientific advances during a feedback seminar and by the presentation of documents.

SUMMARY

Agriculture in the Highlands of Madagascar is primarily family-based, based on farms made up of households whose livelihoods are mainly linked to agricultural activities (annual or perennial crops, livestock, fishing, forestry, first agricultural transformation) carried out mainly with family work. These family farms are more or less integrated into the markets and value chains which strongly contribute to food security and to the economic growth of the country.

This agriculture is subject to several constraints that severely limit its productivity and sustainability: growing demography, land saturation, infrastructure in poor condition, poorly accessible markets and fluctuating and often poorly remunerative farm product prices. There are also many biophysical (low soil fertility, climatic hazards, pests and diseases) and economic risks, and in the event of a shock, support to overcome them is virtually non-existent. The factors of production of farms, and in particular agricultural land, are sometimes particularly low (60% of farms in the Vakinankaratra Highlands are less than half a hectare), making it difficult to improve the productivity of family labor. Added to this is the poor quality of soils in general (low natural fertility, aluminum toxicity, erosive phenomena). In addition, climate change reinforces the constraints caused by rainfall fluctuations and by promoting the development of pests and diseases (insects, diseases, etc.) due to the significant increase in temperatures. This results in employment and malnutrition problems for a large part of the agricultural and rural population (+ 50% of children <5 years old are malnourished). The smallest farms do not or hardly get out of poverty, because the family labor force is undervalued and the agricultural products available, after sales, for household consumption, as well as non-agricultural income, are insufficient.

In this actual context of climate change, food insecurity, population growth, negative impact on environment and natural resources, and loss of biodiversity, agriculture is rapidly changing. A great importance is now given to ecological processes occurring within agrosystems, in what is called **agroecology**. Generally, agroecological practices are based on the manipulation of the aboveground biodiversity, on the management of organic matter as the main source of nutrients, and on the reduction of soil tillage. A poor attention is given to **soil ecological processes** (i.e. soil functions) and the belowground biodiversity in agricultural practices despite its recognized high potential to enhance ecosystem service delivery and promote multiple ecosystem functions simultaneously. Soil function restoration (SFR) as a way of **ecological intensification**, is mostly relevant for tropical smallholder farmers developing their crops on fragile and poor soils, with low inorganic fertilizer inputs and under climate change, such as in the Highlands of Madagascar. The agroecological approach based on ecological intensification of crops and on the integration of agriculture and animal husbandry within farms seems the most appropriate way to sustainably develop this family agriculture in the Highlands.

Our project aimed to provide SFR practices based on local and scientific knowledges, in order to increase both agronomic, socio-economic and ecological performances of agroecological agrosystems. We explicitly aim to (i) assess local knowledge and farmer's interventions on SFR (WP1), (ii) improve our scientific knowledge of SFR on diverse soil and plant functions (WP2), (iii) test at field level various SFR practices based on farmer's and scientist's knowledge (WP3), (iv) evaluate the impact of SFR practices in terms of agronomic, socio-economic and ecological performances (WP4), and (v) disseminate our results, mainly: SFR practices to farmers and stakeholders (innovation platform), knowledge on soil functioning in agroecology for students, indicators of soil functioning for scientists and users; a dedicated website (WP5).

Our project focused on rainfed rice cropping systems in the Highlands of Madagascar, rice being a major crop in the World, in the tropics and especially in Madagascar. Our approach combining local and scientific knowledges is relevant to ensure the diffusion of adoptable SFR practices to farmers. The measurement of agronomic, socio-economic and ecological performances is also original and allows proposing the 'best' practices to farmers. The project was based on a multi-disciplinary consortium located in Madagascar. Two sites in Madagascar were considered, both on the Highlands and differing from climate, soil and farming practices; both were studied in on-going projects by our consortium. A better inclusion in tropical agroecological systems of SFR practices based on traditional and scientific knowledge could improve agronomic performances and the provision of agrosystem services such as nutrient cycling, carbon sequestration, farmer's livelihood, and food security.

The SECuRE project has enabled an increase in socio-economic knowledge and the level of intensification of agricultural operations in the Highlands of Madagascar, an improvement in scientific knowledge of soil ecological functioning and soil-plant relationships in cultivated environments, a sharing of knowledge with farmers to co-construct new knowledge and co-design new practices.

A socio-economic survey was carried out in 323 farms (in the two study regions) to provide knowledge on the socio-demography of households, productive and non-productive assets, on- and off-farm activities, income and soil fertility management practices. The results were, among others, published in 3 articles in the 'Journal de l'Agroécologie' and in a booklet entitled 'Comparative analysis of soil and crop management at farm level of two sites: Mandoto in the Middle -West of Vakinankaratra and Arivonimamo in the Highlands of Itasy' (booklet printed in 200 copies and distributed to decision-makers and NGOs). Furthermore, a peer-reviewed paper (Razanakoto et al.,2020) highlighted that in the most land intensive cultivation area, farmers' practices still remain based on organic fertilizer while they provide the highest agricultural incomes thanks to urban market links.

Scientific knowledge has also progressed during this project concerning on the one hand the role of key soil organisms on the growth of cultivated plants and on the other hand on fertilization practices based on complex assemblages of fertilizing materials. Several articles concerning the role of earthworms have been published in indexed journals demonstrating the positive effect of these organisms on nutrient recycling, soil aggregation, carbon storage and the regulation of diseases such as rice blast, and ultimately on the growth of rice. These organisms appear as a particularly interesting path of ecological intensification. The work carried out as part of M. Raminoarison's thesis (the only thesis funded by the SECuRE project) confirmed the significant mineral deficiency of Highland Ferralsols, mainly in phosphorus but also in calcium, nitrogen and magnesium. These soils, in fact, cannot be corrected at a social cost by NPK fertilizers which do not remove all the constraints; this reinforces the idea of mainly fertilizing soils / crops with organic matter containing a large panel of nutrients. Original approaches have made it possible to define functional groups of fertilizers (i.e. materials having comparable effects when assembled with other materials) and have shown that certain assemblages are very interesting for the growth and yield of rice, reinforcing the feasibility of ecological intensification. The assemblages of organic materials make it possible to provide multiple chemical elements which are diffused. Some of these assemblages were tested in the field in a randomized trial for which the agronomic and ecological performance of the soil, and the farmers' perception could be assessed. A original multi-criteria indicator, built in this project, made it possible to finely discriminate the effect of agricultural practices on the functioning of an agroecosystem and their acceptability by farmers. Information on fertilizers have been gathered in a booklet distributed to many farmers.

During the project, since the early beginning, we developed strong participatory activities with farmers from the two farmers' network, contributing to produce co-learning among farmers and scientists. For instance, we co-built the criteria of self-assessment of the SFR, we included into the field trial 2 proposals from the farmers that they wanted to experiment, we invited farmers to assess the state of the rice development on the trial area, we confronted results of the farmer's assessment with several scientific measures.

The project outputs and outcomes generated raise issues about multicriteria assessment, trade-offs between several stakeholders having different perspectives, values, knowledge and affordances. It raised also the question about how to support scaling mechanisms: as many famers declared being interested in changing practices (like producing their own vermicompost and compost), they also raised numerous blockages that hinder substantial changes in farming practices (like lack of cash to start new cropping activity, lack of evidence about climatic risks, etc.). This highlights the mechanisms to support and develop an ecosystem of relevant and timely support services providers able to support such complex changes encompassing several types of services: advisory services, access to equipment, credit, information, institutional support and access to market, capacity building, etc. To start with, we suggest pursuing to support co-learning about organic fertilization but involving other types of stakeholders so that the scale of the agricultural innovation system will be addressed.

SCIENTIFIC REPORT

I. PROJECT CONTEXT

Agriculture in the Highlands of Madagascar is primarily family-based, based on farms made up of households whose livelihoods are mainly linked to agricultural activities (annual or perennial crops, livestock, fishing, forestry, first agricultural transformation) carried out mainly with family work. These family farms are more or less integrated into the markets and value chains which strongly contribute to food security and to the economic growth of the country.

This agriculture is subject to several constraints that severely limit its productivity and sustainability: growing demography, land saturation, infrastructure in poor condition, poorly accessible markets and fluctuating and often poorly remunerative farm product prices. There are also many biophysical (low soil fertility, climatic hazards, pests and diseases) and economic risks, and in the event of a shock, support to overcome them is virtually non-existent. The factors of production of farms, and in particular agricultural land, are sometimes particularly low (60% of farms in the Vakinankaratra Highlands are less than half a hectare), making it difficult to improve the productivity of family labor. Added to this is the poor quality of soils in general (low natural fertility, aluminum toxicity, erosive phenomena). In addition, climate change reinforces the constraints caused by rainfall fluctuations and by promoting the development of pests and diseases (insects, diseases, etc.) due to the significant increase in temperatures. This results in employment and malnutrition problems for a large part of the agricultural and rural population (+ 50% of children <5 years old are malnourished). The smallest farms do not or hardly get out of poverty, because the family labor force is undervalued and the agricultural products available, after sales, for household consumption, as well as non-agricultural income, are insufficient.

In this actual context of climate change, food insecurity, population growth, negative impact on environment and natural resources, and loss of biodiversity, agriculture is rapidly changing. A great importance is now given to ecological processes occurring within agrosystems, in what is called **agroecology**. Generally, agroecological practices are based on the manipulation of the aboveground biodiversity, on the management of organic matter as the main source of nutrients, and on the reduction of soil tillage. A poor attention is given to **soil ecological processes** (i.e. soil functions) and the belowground biodiversity in agricultural practices despite its recognized high potential to enhance ecosystem service delivery and promote multiple ecosystem functions simultaneously. Soil function restoration (SFR) as a way of **ecological intensification**, is mostly relevant for tropical smallholder farmers developing their crops on fragile and poor soils, with low available chemical inputs and under climate change, such as in the Highlands of Madagascar. The agroecological approach based on ecological intensification of crops and on the integration of agriculture and animal husbandry within farms seems the most appropriate way to sustainably develop this family agriculture in the Highlands.

The overall objective of the SECuRE project was to provide Soil Function Restoration (SFR) practices based on local and scientific knowledges, in order to increase both agronomic, socio-economic and ecological performances of agroecological agrosystems in a tropical context. We hypothesized that innovative cropping practices improving SFR can promote major ecosystem functions, i.e. nutrient cycling, carbon storage, control of pathogens, plant production, and resistance to climatic stresses, performed by soil biotic diversity and fertilizing assemblages. SFR aims to optimize current farmer's practices and propose innovative practices that will promote soil habitat in order to increase soil functional diversity and intensify associated soil and plant functions. It is part of agroecological restoration. For that purpose, optimized and innovative SFR practices were:

1. The use of original organic inputs with high agroecological performances such as vermicomposts
2. An efficient combination of existing organic and mineral fertilizers promoting plant functions
4. Biofertilization, i.e., inoculation of key soil organisms to restore some soil functions
5. The use of crop varieties that best respond to innovative SFR practices

Specific objectives were:

1. to assess farmer's interventions on soil restoration in two regions of the Highlands
2. to improve our knowledge of the effect of key soil organisms on diverse plant functions,
3. to test various restoration practices based on farmer's and scientist's knowledge,
4. to analyze the impact of soil restoration practices in terms of agronomic, socio-economic and ecological performances through an innovative original method,
5. to support co-learning and dissemination of our results with stakeholders: restoration practices to farmers, knowledge on soil functioning in agroecology for students, indicators of soil functioning for scientists and users.

6. to bring generalizable knowledge on soil/plant functions in agroecology and more contextual outputs in the case of Malagasy family agriculture with "custom-made" cropping systems where farmers are at the center of the innovation systems.

We explicitly aimed to (i) assess local knowledge and farmer's interventions on SFR (WP1), (ii) improve our scientific knowledge of SFR on diverse soil and plant functions (WP2), (iii) test at field level various SFR practices based on farmer's and scientist's knowledge (WP3), (iv) evaluate the impact of SFR practices in terms of agronomic, socio-economic and ecological performances (WP4), and (v) disseminate our results, mainly: SFR practices to farmers and stakeholders (innovation platform), knowledge on soil functioning in agroecology for students, indicators of soil functioning for scientists and users; a dedicated website (WP5).

II. METHODOLOGY

*** Methodology WP0 'Project management'**

For each WP, we proposed a couple of leaders in order to maintain as much as possible equilibrium between Malagasy and French partners, and between genders. This was really efficient and facilitated management and project progress. Many meetings of the management team (project coordinator and WP leaders) were organized, especially during the first year of the project. The kick-off meeting was organized in two stages: the first time in distance (visioconference) and the second time in the field, in Madagascar with site visits, in the presence of the steering committee. Several other face-to-face meetings were held in Madagascar to evaluate the progress of the project.

*** Methodology WP1 'Local-based farmers' knowledge on soil function restoration'**

This WP was conducted by a mixed team composed of socio-economists and agronomists in order to apply a holistic approach at different levels of the different farm activities to assess local based farmers' knowledge on soil function restoration. Different tools were applied on two contrasted socio-agroecological areas, in the Mandoto district 800 to 1300 asl (Vakinankaratra region, called '**Ivory'** in the project) and in Arivonimamo district 1400 to 1600 asl (Itasy region, called '**Imerintsiatosika'** in the project) (Appendix 1).

A farm survey, in a sample of 323 farms, was carried out in the two municipalities. Two *fokontany* (smallest administrative division) per municipality were selected in order to represent the diversity of agricultural situations. The random selection of farms in the fokontany ensures statistical representativeness (Appendix 2). The data collected comprised a socio-demographic description of the household, information on productive and non-productive assets, on- and off-farm activities and income (calculated) in order to link them with soil fertility management practice of farmers. For more details, a permanent partnership with two farms' networks based on peasant and scientific knowledges was applied to assess organic flows at the farm level for each main cropping system, to determine manures quality and to conduct multi-local participatory experiments.

*** Methodology WP2 'Scientific knowledge on soil function restoration'**

Action 1. Characterization of fertilizer materials and soil properties. First, we sampled 19 (organic, mineral, rock-based) fertilizers from Madagascar (Appendix 3). The different fertilizers represent the diversity of organic and mineral materials present in the Highlands of Madagascar. Some came from peasant farms, others were commercial products available in the close villages. We then characterized the physicochemical and biological properties of fertilizers (e.g., water, total N, C, P, S, Ca and Mg contents, pH, organic matter content, carbon-fractions). The quantification of diffusible P-ions has been carried out using isotopic dilution; this technique allows to assess plant P availability for a period of several months or years.

Action 2. Characterization of the beneficial activity of soil organisms on soil and plant functions. This step takes the form of a series of experiments in microcosms and mesocosms in a greenhouse under controlled conditions where soil organisms (earthworms, nematodes, mycorrhizae) were handled. We tested (i) the coupled effect of earthworms and silica on plant growth, nutrition and blast disease severity, (ii) the effect of mycorrhizae on 10 rainfed rice cultivars, (iii) the effect of nematodes and earthworms on rice P nutrition and plant-available soil P (by isotopic dilution technique), (iv) the cross-effects of fertilizers, earthworms and mycorrhiza for several rice cultivars. For all these experiments, several soil and plant variables were assessed such as plant growth and nutrition and soil nutrient content.

Action 3. Identification of soil microbe- and plant-limiting nutrients. Two nutrient-omission experiments have been conducted to assess the nutrients that mostly limit soil microorganisms and plant growth. We tested the omission of N, P, Ca, Mg, K, S, Si and micronutrients. Additional analyses of bacterial phyla were carried out to identify the bacterial and fungal families that respond to mineral fertilization. We also analysed soil nematode as a biological indicator of soil health.

Action 4. Assemblages of fertilizers and assessment of fertilizing functional groups. We tested 170 innovative fertilizer assemblages in 5 kg soil cylinders. We analysed plant biomass, growth and photosynthetic activity, nutrient (N, P, K, Ca, Mg, C) content and soil properties. An '*a posteriori*' combinatorial model was used to characterize the functional groups of fertilizers using FunctClust package under R. This experiment was repeated in field situation in Itasy and rice yield was assessed.

Action 5. Testing rice genetic diversity and soil organisms and fertilizers. Greenhouse experiments with 10 rice cultivars from FOFIFA genetic improvement program were set up either with mycorrhiza, earthworms or different fertilizer assemblages.

*** Methodology WP3 'Soil function restoration field trials'**

The trials were carried out at (i) Imerintsiatosika (Itasy) for three growing seasons: 2017-2018, 2018-2019 and 2019-2020 and (ii) Ivory in the mid-west of Vakinankaratra for the first two cropping seasons of the project. For year 1, the trial (4 blocks) was exclusively focused on the restoration of soil habitat with the use of 16 SFRs practices (each plot is 16 m2), based on organic, mineral amendments and their assemblage (Appendix 4). For year 2, the focus was on the rehabilitation of the functional diversity of the soil with the inoculation of soil-plant mutualists: earthworms of the species *Pontoscolex corethrurus* (at a density of 50 worms/m², meaning that more than 70,000 individuals were collected and inoculated) and endomycorrhizae *Rhizophagus irregularis* (at a dose of 2 spores/seed). New peasant (identified during workshops carried out in year 1) and scientific SFRs practices were added. Therefore, in all, 25 SFRs were tested on Itasy and 22 SFRs on Ivory (Appendix 4). For year 3, the 25 SFRs were renewed on the Itasy site only in order to assess, in the medium term, the effect of the restoration of soil habitat and the rehabilitation of the soil functional diversity on agronomic and ecological performance. Rice varieties adapted to each site were maintained for the duration of the experiment: Chhomrong Dhan in Itasy and Nerica 4 in Ivory. Various observations and measurements were carried out according to the stages of phenological development or rice growth (Appendix 5). During the first growing season, the coordination and harmonization of the measurements carried out on the two sites was difficult but was corrected during the implementation of the experiment of the second growing season (2018 -2019).

*** Methodology WP4 'Evaluation of soil function restoration'**

The methodology implemented to evaluate SFR in terms of agronomic performance, soil ecology performance and farmers' perception in order to propose a global multicriteria indicator was as follows:

1- Choice of a homogeneous dataset to develop the approach: we focused on the Itasy trial in year 2 of the 16 SFRs launched in the first year of the project.

2- Constitution of the dataset: the dataset consisted of 82 soil ecological descriptors, 54 agronomic descriptors and 8 social-economic descriptors. The ecological and agronomic descriptors corresponded to measurements carried out on the agronomic trial, while the social-economic descriptors were taken from the peasant perception workshops conducted under WP5.

3- We then followed the 4 stages of constructing an indicator: (1) the selection of descriptors, (2) the scoring, (3) the weighting and finally (4) the aggregation. At each stage we tested methods ranging from statistical analysis without *a priori* to the opinion of an expert based on both his experience and his knowledge of the bibliography.

4- The selection of ecological and agronomic descriptors made it possible to eliminate all descriptors not impacted by the practices deployed on the 16 SFRs after 2 years of setting up the trial, and which could generate background noise in the final indicator. Scoring makes it possible both to normalize the values obtained for each measured variable retained (between 0 and 1) as well as their direction of variation (the more = the better, or the less = the better, or the better corresponds to an optimum). Weighting makes it possible to give more importance to one descriptor compared to another in the final indicator, either because it allowed to differentiate very well the different practices, or because it accounts for a very important ecosystem function with regard to the objectives to be achieved. The final weighted scores were then aggregated by calculating averages either globally for each performance (ecological, agronomic and socioeconomic) or by functions defined within each performance

(Ecological: maintenance of physicochemical fertility, carbon dynamics, recycling of nutrients, regulation of crop pests and maintenance of biodiversity; Agronomic: plant growth, biomass, yields, grain quality and straw quality).

*** Methodology WP5 'Networking, co-learning and dissemination of knowledge on soil function restoration'**

The objective of WP5 was to support co-learning and dissemination of our results with stakeholders: restoration practices to farmers, knowledge on soil functioning in agroecology for students, indicators of soil functioning for scientists and users. To ensure co-learning mechanism we developed a participatory approach with stakeholders involved in the project: farmers-interviewees, farmers from the two farmers' network; technicians; students and researchers. The participatory approach took different levels according to the stakeholders; from sharing of information and results, to co-building of protocol and co-evaluation of SFR.

- With the two farmers-networks: (i) (first workshop) we co-build the criteria of self-assessment of the SFR, based on their local knowledge about the soil functioning and organic fertilizers they knew, or the potential responses from the rainfed rice using such fertilizers; (ii) we included into the field trial 2 proposals from the farmers that they wanted to experiment, which were actually similar to some fertilization practices they implemented; (iii) (second workshop) we invited the farmers to assess the state of the rice development on the trial area, and each SFR performance using their own descriptors that we gathered into 5 crop indicators and 8 SFR indicators; (iv) we built an aggregated index to represent the farmers' local knowledge about SFR performance; (v) (third workshop) we presented the results of the farmer's assessment and confronted to several scientific measures, in order to discuss: the cross-results between farmers' perception and few scientific measures, and necessary trade-offs related to strategical choice of SFR; (vi) we assessed individual learning mechanisms developed by farmers from the farm network, before and after the third workshop.

- With advisory and extension services: technicians and advisors from other NGOs and local associations were involved at several steps of the projects: (i) share and discussion of the methodology of WP1-3 and 5; (ii) identification of the farmers to build the farmer's network in Imerintsiatosika with advisors and technicians from Agrisud NGO, half of the network were part of Agrisud network. The farmer's network was already existing in Ivory and was the result of long-lasting partnership with GSDM NGOs and other local associations, which was pursued within SECuRE project; (iii) invitation to take part of the several workshops from WP1 and WP5, as facilitators (like facilitating group sessions) or as attendees; (iv) received the booklets and guides produced by the project; (v) invited to the national workshop hold in Antananarivo in February 2021.

-With farmers and administrative representatives from the two study areas; we shared the results of the household survey and discussed the practical perspectives (see WP1).

- With students we contributed to capacity building through supervision of internships, one thesis, and developed pedagogical materials (movies and scientific soil ecological analysis methods with the implication of students).

- With scientific communities we disseminated our results through secondary data and document, scientific publications and communications at national and international levels.

- With large audience and decision makers, were shared our results and recommendations through a national workshop, movies, technical and scientific documents available on our website.

III. RESEARCH RESULTS

*** Results WP1 'Local-based farmers' knowledge on soil function restoration'**

Some of these WP1 results have been published in Razanakoto et al. (2020, Outlook on Agriculture 50, 80-89) and in three papers published in the Journal de l'Agroécologie

• Results of the survey: Farmers' adoption and description of fertility management techniques (results synthesized in the booklet 'Comparative analysis of soil and crop management at farm level of two sites: Mandoto in the Middle -West of Vakinankaratra (Ivory) and Arivonimamo in the Highlands of Itasy' (Imerintsiatosika), available on the SECuRE website)

Among the techniques pre-identified by experts as being able to contribute to soil fertility management, the level of adoption is very high in both zones for organic fertilizer application, legume cultivation as well as rotation and crop associations. There were some differences with very high rates in one zone and slightly lower rates in the other for inorganic fertiliser application, Aroloha/Aroriaka, fallow, agroforestry, deep ploughing, restitution of weeding products and crop residues. Other techniques such as farm waste recycling, green manure, conservation agriculture, vegetation burning, grass strips, terracing, stone barriers, and land transfer are little or not practised by farmers. The lack of resources or capital (financial, human, physical, land, etc.) is a major factor blocking the adoption of these techniques.

Almost all farmers share the same perception of fertility for techniques such as fallow, organic fertilization, farm waste recycling, mineral fertilization, crop rotations and deep tillage. However, perceptions can be contradictory for other techniques. For example, the return of weeding products and crop residues does not necessarily contribute to this objective of improving soil fertility for some farms in Imerintsiatosika. However, when these products are not returned to the soil directly, they are collected for animal feed or litter to contribute to soil fertility through organic manure. This highlights a strong integration of agriculture and livestock.

- Results of the survey: the use of organic fertilizer

The use of organic fertilizers is widely practised in both zones; farmers apply organic fertilizers on at least one their cultivated plot.

- Different types of organic fertilisers: There are different types of organic manures (OM). The main ones are mixed manure and cattle manure (72% of the total of organic fertiliser produced in Mandoto and 83% in Imerintsiatosika) (Appendix 6). Farms with several species of livestock mix the manure and often add household waste, ash and in some cases other crop residues or waste (Appendix 7). Manure is therefore an organic fertilizer whose composition and quality vary greatly from one farmer to another. We also note, particularly in Ivory, the importance of a traditional farm waste called zezi-pako (made up of plants, especially used in small farms), with 16% of the OM (Appendix 6).

- Production and availability of organic fertilizers at farm level: The average amount of organic fertilizer available in a farm is 2.9 tons in Imerintsiatosika and 2.1 tons in Mandoto. This availability is a function of: (i) the quantities produced (on average 2.2 tons per farm in Imerintsiatosika and 1.9 tons in Mandoto), via manure and farm waste recycling practices; (ii) market or non-market (barter or donation) exchanges (Appendix 8).

- Allocations of organic fertilizers: Regarding the allocation of OM, farmers fertilise first the most demanding and remunerative crops: (i) rainfed cereals notably rice and maize and market gardening crop (which are very marginal) in Ivory. Organic fertilizer is added at a rate of 4,000 kg/ha in pure culture and 700 kg/ha in associated culture of rice and maize (Appendix 9 and Appendix 11); (ii) crop intended for sale as vegetables, potatoes, beans, sweet potatoes, taros in Imerintsiatosika. Organic fertilizer is added at a rate of 4,500-7,000 kg/ha (Appendix 10). Other crops benefit from fertilisation either through crop associations or rotations. Rice in lowland rarely receives fertilizer (Appendix 12).

- Use of inorganic fertilizers and ash: The use of inorganic fertilisers varies between both zones. It is widely used in Imerintsiatosika. Nearly 90% of the farms apply on average a dose of 50-100 kg per ha (Appendix 10), and almost always as a complement to organic manure. In Ivory, one farm out of two uses less than 60 kg per ha. The use of ashes directly on the plot, without going through farm waste or manure, is a common practice in Imerintsiatosika. According to some producers, in addition to providing fertilizing elements, the ashes combat pests and diseases.

- Share of fertilization in production costs: The study showed the low cost of fertilization in the production of annual crops, with an average of 4% of the gross product in Ivory and 11% in Imerintsiatosika, and with organic fertilizer accounting for 78% of fertilization costs. Thus, the impact of fertilisation on the cost price is low.

- Results of the farms' networks

- Performance of different organic fertilizers in farm-scale multi-local experiments: Multi-local experiments in partnership with farmers on 20 (in Ivory) and 15 (in Imerintsiatosika) reference farms were carried out to test the performance of different organic fertilizers on rainfed rice (Appendix 13): (i) we noticed a potential of these fertilizers for the correction of soil acidity; initial soil pH was around 5 for both sites and organic fertilizer pH ranges from 6.9 to 9.6, (ii) Regarding crop nutrition, organic fertilizers seem to be richer in nutrients (nitrogen and phosphorus) in Imerintsiatosika than in Ivory due to the use of more added products to cattle-based manure, (iii) Regarding rice yield, we noticed a better performance in Imerintsiatosika compared to Ivory.

- Farmers' scoring of different organic fertilizer: this showed, based on different selected criteria (Appendix 14), that: (i) inorganic fertilizers are viewed as costly and inefficient for soil fertility in the long term, (ii) the improvement of organic fertilizer is feasible through their conservation (i.e. improved manure means storage manure improvement through cattle excreta conservation).

*** Results WP2 'Scientific knowledge on soil function restoration'**

Some of these WP2 results have been published in international journals: Raminoarison et al., 2020. Journal of Plant Nutrition, 43(2), 270-284. Ratsiatosika et al., 2021. Applied Soil Ecology, 103958. Trap et al., 2021. Applied Soil Ecology, 160, 103867. Ratsiatosika et al., 2021. Agriculture, 11, 60. Blanchart et al. 2020. Applied Soil Ecology, 145, 103341.

Action 1. Characterization of fertilizer materials and soils: The data showed that the soils were acidic, poor in carbon and nutrient, but rich in Al and Fe (Appendix 15). Regarding the characterization of fertilizers, we noticed the particularity of zebu horn powder which contains remarkably high contents of N and C, and whose N mineralization occurred slowly. Only 50% of the C introduced by this fertilizer was mineralized during the incubation period (150 days). We also observed the richness in total P and Ca of bat guano, the high total Mg content in dolomite, the high K content in Eucalyptus ash and cattle manure. It is important to note that Eucalyptus ash also contains significant amounts of total Ca, Mg and P. We found high cellulose fraction in cattle manure, hull ash and rice straw. With respect to the C and N mineralization, dolomite and hyperfos (rock-based fertilizers) mineralized very quickly compared to other materials and showed C mineralization extremely greater than 1 g C-CO_2 g^{-1} of C added after 150 days of incubation. On the other hand, products made from animal faeces (cattle faeces, poultry faeces), composted or not, exhibited weaker mineralization kinetics. Zebu horn and guano have the highest early N mineralization while poultry manure has the lowest early N mineralization. While the contributions of zebu horn, compost from Andralanitra and poultry manure caused a net N mineralization, dolomite and guano induced a net N immobilization.

Action 2. Characterization of the beneficial activity of soil organisms on soil and plant functions: Regarding the coupled effect of earthworms and silica on the plant growth, nutrition and blast disease tolerance, the results showed a very significant positive cross-effect of earthworm and silica on plant growth and disease tolerance compared to chemical fertilizer application. Our results validated the hypothesis that a dual treatment of earthworm inoculation and Si fertilization in a nutrient-poor tropical soil confers a higher tolerance of rainfed rice to blast disease. The supply of macronutrients (NPK) altered this positive belowground-aboveground relationship by favouring the phenomenon of N-induced susceptibility. The aboveground plant C:N ratio of 15 is a threshold below which any increase in N per C unit likely enhances blast disease (Appendix 16). The role of belowground interactions to counteract agricultural dysfunctions is supported by our study. We also observed high effect of earthworms on plant functions and growth, but this effect was strongly variable according to rice cultivar (see Action 5). We also observed that *P. corethrurus* significantly increased rice shoot biomass (+26%) and P nutrition (+65%). We estimated that the orthophosphate ions released due to earthworm mortality contributed to 30% of the L-value increase. We attributed the remaining 70% increase to the solubilization of native soil P during its transit through the digestive tract.

Action 3. Identification of soil microbial and plant-limiting nutrients: For Itasy soil, we observed a strong limitation in C and P (co-limitation) for microorganisms and soil fauna, then a co-limitation in N and S. We did not observe any limitation in Ca, Mg, K or micronutrients. Concerning plants, we observed a strong limitation in P and Ca, then in S and N for the soil of Imerintsiatosika (Appendix 17). For the soil from Ivory, rice was mostly limited by P and N. We thus concluded that upland rice growth in Ferralsols from Madagascar was found to be constrained by multiple nutrient co-limitations. P, Ca, N and Mg appear the most important nutrients limiting the growth of rice. However, the effect of Ca and Mg depletion was dependent on the soil origin. Additionally, we did not exclude the potential role of Al toxicity on rice growth under particular nutrient deficiencies and low pH.

Action 4. Assemblages of fertilizers and assessment of functional groups: The combinatorial approach by *a posteriori* classification showed that the performance of the assemblages was mainly explained by the effect of the composition of the fertilizers which constitute the assemblages. Thus, the individual capacity of the materials present in an assemblage greatly influences the performance of the assemblages. Although the interaction effect is not correctly modelled, our results show that, on average, interactions between fertilizers increase rice grain production. The fertilizers can be divided into three classes according to their effects on the performance when they are assembled. Materials composed of {Vermicompost}, {manure, compost, park crumb}, and {ash, chicken manure, pig slurry, NPK} induce positive effects by improving grain yield when they are incorporated into a mixture, and the best patterns of assemblies are obtained with their combination. The materials characterized by {ash, dolomite, hyperfos} tend to lower the production in grains, in assemblage. The best assemblage patterns can thus be identified from knowledge of the stimulatory or inhibitory effects of fertilizers in assemblages. The sustainability of the agricultural system also requires the maintenance of the long-term fertility of the soil.

Action 5. Testing rice genetic diversity and soil organisms and fertilizer: We first observed contrasting effects of mycorrhizae (seed treatment) on plant growth and nutrition according to rice varieties. The effect of earthworms on rice cultivars has also been characterized in the same way. Plant nutrition and growth were significantly improved in the presence of earthworms for all cultivars compared to the control treatment. However, the magnitudes of earthworm effects on plant traits were strongly variable and were dependent on specific rice cultivars. Agronomic and phylogenetic distance matrices were computed using agronomic data and available phylogenetic data of the rice cultivars. We did not detect significant correlations between cultivar responses to earthworm inoculation and agronomic or phylogenetic distances. Our results suggest that (i) the ability of rice to exploit beneficial interactions is influenced by its genetic background, but (ii) the loss of earthworm-interactive abilities of rice crops is independent of the genetic distance among cultivars and breeders' agronomic criteria. We also observed contrasting response of rice cultivar to use 4 different fertilizing practices.

*** Results WP3 'Soil function restoration field trials'**

The results obtained during the three years of experiments have brought out the following main points:

- In Imerintsiatosika, the grain yield remains minimal (with an average yield of around 0.02 t/ha) in the absence of fertilizers. Conversely, we observed a rice production, although very small, in the absence of amendments in Ivory, with an average yield estimated at 0.32 t/ha in year 1 and 0.60 t/ha in year 2. For both sites, the addition of soil amendment each year significantly increased biomass production and yield. For Imerintsiatosika, the total biomass (straw and grains) varied on average between 1.04 and 2.73 t/ha in year 1, between 1.99 and 5.74 t/ha in year 2, and between 2.37 and 7.90 t/ha in year 3, respectively (Appendix 20, 21, 22). For Ivory, the total biomass was estimated between 0.78 and 2.41 t/ha in year 1 (Appendix 18). Then, a significant increase was recorded in year 2, with a biomass between 1.65 and 9.97 t/ha (Appendix 19).

Regarding SFRs (refer to the list of SFRs in Appendix 4), those based on mineral fertilization (SFR8 and SFR21) showed a drop in grain yield for each cropping season in Imerintsiatosika. This confirms that mineral fertilization (at the rates used) is not an alternative to sustainably manage soil fertility and rice production in this area. In Ivory, among the 16 SFRs studied, SFR8 was in 5th position with a grain yield evaluated at 0.86 t/ha in year 1 (Appendix 18). In year 2, production doubled with a grain yield value of 1.77 t/ha (Appendix 19). The difference between production (straw and grain biomass) in both areas might be linked to the difference in agronomic performance between the varieties used and also to differences in the soil physicochemical characteristics. The pH of the control soil of Ivory was higher (5.3) than that of Imerintsiatosika (4.3). Also, Ivory's SFR8 has a higher soil pH (6.0) than Itasy's (4.3).

- In Imerintsiatosika, the innovative SFRs proposed by scientists are generally the most efficient agronomically, this is also the case for SFR17 which was a practice proposed by farmers' in year 2. The results on the average grain yield during the three years of experimentation show that SFR17 presents the highest yield, followed by SFRs with high rates of inputs (18 t DM/ha; SFR18, SFR19, SFR22), then SFRs at 6 t DM/ha, with the exception of SFR6. This latter SFR has a grain yield of the same level as those of the "peasant" SFRs at a dose of 3 t DM / ha, the agronomic performance of which appears to be weaker. Regarding the controls, whether for the positive controls (SFR8 and SFR21) or for the negative control (SFR16), their agronomic performance remains very poor (Appendix 23). For high-dose SFRs, the effects of SFR18 and SFR19 are clearly demonstrated from the first year of input. During year 2, during which no addition was made, SFR18 maintained its high agronomic performance, unlike SFR19. SFR22, the effect of which was less noticeable during the first year of application, shows a grain yield similar to that of SFR18 in year 2. Regarding SFRs at 6 t DM/ha, SFR24 was the most efficient in terms of average grain yield. It is followed by the SFRs made up of organic fertilizers alone (SFR5, SFR7, SFR4) and the SFRs based on the assemblages of organic and mineral fertilizers (SFR15, SFR13, SFR14, SFR10, SFR9, SFR23, SFR25). In terms of assemblages, SFR15 was still among the best performing agronomically over the three years of trials. For SFRs composed of assemblages (SFR12, SFR19, SFR25), a drop in grain yield was noted over time. This is probably due to the poor agronomic performance of the compost (SFR6) which follows the same trend as the SFRs at 3 t DM/ha. However, in Ivory, compost was classified in 3rd position in terms of rice grain yield, measured in the second cropping season (Appendix 19).

- In general, the SFRs that show better agronomic performance also showed better ecological performance, whether in Itasy or Ivory (see WP4). For the Imerintsiatosika site (year 2), the more the amendment rate increases, the more the pH increases, except for the case of SFR17, which has a high pH despite the low amendment rate. Regarding the bioavailable soil P content, the SFRs with a high input (18 t DM/ha), the SFR15, the SFR17 and the SFRs based on the assemblages of organic and mineral fertilizers (SFR11, SFR23 and SFR24) showed the highest values. High-dose input SFRs also resulted in higher basal soil respiration compared to other SFRs. Regarding the decomposition rate of green tea, the maximum value (81%) was recorded on SFR5 (improved manure). Similarly, the maximum decomposition rate of bait lamina (30%) was noted on this treatment, which seems to show greater biological activity. For the POxC measurement, SFR4 (traditional manure) showed the highest value. Despite the poor agronomic performance of SFR6 (compost), its ecological performance is interesting. The overall bacterial metabolic activity and microbial P content were measured at maximum on this treatment. In addition, the highest density of *P. corethrurus* was noted on SFR6. It is very interesting to note that most of soil biological parameters were positively correlated with the indicator of agronomic performance (details in WP4) which is one of the major results of the project (Appendix 24). The inoculation of earthworms (considered here as an agricultural practice) was relatively efficient since earthworm biomass at the end of year 2 ranged from 0 to 80 ind.m^{-2} in inoculated plots, against almost 0 ind.m^{-2} in non-inoculated plots (except SFR3 with 25 ind.m^{-2}). Earthworms developed very well in SFR6 and SFR10 and did not develop well in SFR4, SFR13, SFR14, SFR15 (Appendix 25).

Regarding the limitations of the study, climatic adversities strongly impacted the rice plants on the Ivory site in year 2. In year 3, the Itasy site experienced a fairly substantial dry period after sowing, leading to a stronger subsequent pest attack when the rain arrived. Another major constraint encountered during this 3rd year also lies in the difficulty and complexity of carrying out the various cropping operations from March 2020 due to the Covid-19 pandemic. Consequently, the measurements carried out in year 3 were specifically focused on the agronomic performance and soil macrofauna.

*** Results WP4 'Evaluation of soil function restoration'**

We realized that the statistical approach we used (Stepdisc: Stepwise Discriminant Analysis) made it possible to obtain an indicator that was much more sensitive to practices than methods based on expert opinion. In fact, this method makes it possible to eliminate many descriptors that have little impact and then generate inertia in the final indicator. Experts tend to keep many more descriptors at the screening stage for fear of suppressing information. This statistical method is fast and only selects the most discriminating variables in the system, which eliminates the weighting step.

The two descriptor aggregation methods (direct or by function) did not present any strong differences on the final fully aggregated indicator. So going through this additional step of aggregation by function does not induce a significant bias in the calculation of the final indicator. However, if direct aggregation makes it possible to quickly obtain an overall value on the performance of a practice (useful for an actor in the field), aggregation by function makes it possible to explain the differences in performance between the practices tested (which is very useful for researchers).

The global indicator showed that SFRs composed of multiple inputs (assemblages) are the most efficient both in agronomic and ecological terms, and in particular SFR15 (Appendix 26).

If we project each SFR on two dimensions corresponding to agronomic and ecological performances, we can first see a very good correlation between both performances (Appendix 27). This result confirms the hypothesis of the SECuRE project that by seeking to restore ecological functions in the soils of agroecosystems, agricultural production is also improved (keeping in mind that the causal relationship has not been demonstrated). More precisely, we can compare SFRs with each other. For example, we can see in the figure that the addition of dolomite (SFR9) improves soil ecological performance more than manure alone (SFR4) without this being accompanied by an increase in yield, at least in year 2 (this does not mean that it will not take place, but it can be shifted in time).

If we decompose the axes of agronomic, ecological and socio-economic performance, in the different functions that compose them (Appendix 28), and that we again compare these SFR4 and SFR9, we can notice that the supply of dolomite resulted in better carbon dynamics, improved physicochemical parameters and better maintenance of biodiversity, but not better recycling of nutrients. It is likely that nutrient recycling is the parameter having a shorter-term effect on agronomic functions. This is why we observe so few differences between these SFRs on agronomic performance. The observation of the different components of socio-economic perception, shows that farmers have a good perception of dolomite in terms of its effect on the soil, crop yield, ease of transport and spreading. On the other hand, it seems less accessible than traditional manure and more expensive.

*** Results WP5 'Networking, co-learning and dissemination of knowledge on soil function restoration'**

First of our methodology was to screen farmers' local knowledge about soil functioning, SFR performance and rice cropping. We noticed, for instance in Imerintsiatosika, that the effect on rice production was the main descriptor mentioned by farmers (42% occurrence), but other logistical consideration (accessibility, easy to carry out or to use) were also mentioned (Appendix 29). The effect on soil quality arrived in fourth position.

We then built an index about SFR performance, based on farmers' descriptors and their frequency mentioned in the 2 sites (Appendix 30). Expected effects on rice yield are the more important factors in the two sites, but accessibility arrives in second position in Ivory (15%). Expected effects on soil arrives in second position in Imerintsiatosika (21%), but in third position in Ivory (14%). However, one could expect that cost-related issue would be much more important as perceived by farmers, we noticed that it has been lowly rated in the two sites (6% in Imerintsiatosika and 10% in Ivory). However, accessibility or ease to carry and to spread might be part of the farmers' cost perception, whom disaggregated such composite dimension.

Then farmers' assessment of each SFR, allowed us to compare each SFR, using several indicators (Appendix 31, 32, 33), or the aggregated index (Appendix 34, 35). Compost has been highly rated in both sites, as well as the combination of commonly used organic and mineral fertilizers (SFR3) (Appendix 34, 35). In Imerintsiatosika, mineral fertilizers only (SFR8) has been lowly assessed by farmers, and the complex assemblages of organic manure with other fertilizers (SFR12, SFR13, SFR14, SFR15) have been highly rated. The SFR composed by traditional manure and ashes (SFR10) has been significantly weakly rated, whereas in Ivory the traditional manure and rock phosphate has been weakly rated, which might be explained by the low accessibility to rock phosphate in this area. In Ivory, low amount of pure mineral fertilizer (SFR8) has been highly rated, which might be explained by farmers' willingness to boost rice yield with short term results.

Crossing farmer's perception with selected scientific indicators allowed us to identify gaps between those 2 communities, and then target specific trade-offs to be addressed collectively. For instance, complex assemblages were highly rated by farmers (Appendix 31, blue dots), whereas they did not provide the highest yields. Middle organic inputs (Appendix 31, light green dots), might be a better compromise in terms of yield. Compost has been highly rated by farmers, but provided low yields, which has been discussed with farmers, and might be due to the low quality of the compost used in the trial. This point has been discussed with farmers, and they emphasized the high diversity of compost quality.

Secondly, farmers overestimated the effect on soil of the current fertilization practices (SFR1, SFR2, SFR3), whereas C provided is quite low (Appendix 32). However, they estimated that vermicompost and compost had good effect on soil, but C provided for compost was very low. Again, it might be due to the poor quality of compost on one hand, and to the complex perception of farmers regarding the effects on soil, which encompasses other nutriment and mineral components than C only.

Thirdly the cost calculated by scientists has little variation, except for vermicompost (SFR7), which was a marketed product, very costly (Appendix 33). Farmers also perceived that vermicompost was expensive, however mineral fertilizer (SFR8) was overestimated by farmers whereas it was not expensive. Complex assemblages were perceived as quite costly which was coherent with cost calculation. However, compost was perceived as expensive by farmers whereas is was not too expensive based on scientist calculation. This difference might be due to local price perception about a product which is barely known by farmers. The other SFR (middle or high organics inputs) were perceived as very interesting by farmers whereas their price was not much lower than organic compost or mineral fertilizer. This might be explained by farmers' difficulties to estimate a price when local or own production is possible (preserved or traditional manure), whereas such fertilizers have local value and can be sold or exchanged, which was the price used by scientist.

The third workshops aimed at discussing of trade-offs results between farmers and scientists. The discussion highlighted important issues: limits of the scientific trials, lack of farmers' experience and feedback about complex assemblages or new fertilizers, and the effect of poor soils on yields. Such discussion allowed cross-learning between farmers and scientists.

IV. EMERGING OUTCOMES AND IMPACTS, IMPLICATIONS OF THE PROJECT

The SECuRE project targeted different beneficiaries, according to the nature of the different WP and the integration of WPs results and disseminations. Smallholder farmers involved in the different WP were both actors and the main beneficiaries of the project, the first objective of the project being to co-construct with farmers innovative practices based on the ecological intensification of soil processes. Original results published in international journals targeted the scientific community. Finally, efforts were made to disseminate our results towards other stakeholders such as NGOs and decision makers. Below are the main outcomes of the SECuRE project.

*** WP1 outcomes**

Civil society recognizes that farmers' agricultural practices are agroecological thank to the crop-livestock integration. In both zones, the available factors of production, i.e. land and livestock, positively determine the total income per capita and therefore the level of poverty. The land intensification, mainly through the intensive use of organic fertilization, in Imerintsiatosika is not sufficient to ensure a high income per capita, compared to Ivory. Farms that have the best productivity per unit area are not those that have the most production factors (land and livestock). Crop-livestock integration should then be efficient allowing an increase in productivity per unit area and per capita income while maintaining the sustainability of agriculture. **For NGOs and their technicians**, improving soil health through biological soil restoration offers new perspectives for ecologically-based crop development.

Farmers are sensitive to soil fertility issues. Development activities often proposed fertilization as a technical manual (technical sheet) in relation to the specific needs of the targeted plant. These proposals go against farmers' strategies. Therefore, their dissemination remains low.

In fact, farmers implement a variety of fertility management practices using what exists. They have knowledge and skills that form a solid base of practices on which both design and dissemination of innovations in this area could be based. Some practices that are already well known and used, such as organic fertilizers, crop rotation and/or association, and Aroloha/ Aroriaka, could be improved, reinforced and/or optimized. It is important to make better use of these different types of fertilization through combinations of practices with a pool of fertility strategies based on local and organic resources.

For example, it would be interesting to strengthen the development and promotion of techniques that increase the quantity and quality of available organic manure (improved stalls, farm wasteing, vermifarm waste, etc.). As farmers invest less in money and opt for a labour-intensive strategy, fertility management techniques should be built upon the use of locally available raw materials, rather than on the basis of purchases. However, if economic conditions are favorable (outlets, sufficiently remunerative prices), they may resort to commercial fertilizers, as this study shows.

*** WP2 outcomes**

From a **scientific** perspective, the outcomes of the WP2 are numerous through the publication of the results in scientific papers in international peer-reviewed journals and in international symposiums (see the list of productions). From an applied perspective, our results provide numerous data that can be used to fuel innovative agronomic practices for **farmers**. Our greenhouse and field works conducted on fertilizer assemblages can be used to propose a new agronomical framework for soil fertilization and incorporates reliable scientific knowledge and agronomic benefits that are easily transferable to **farmers** for a co-construction of innovative practices. Different agronomic levers have been tested simultaneously in this WP (rice genetic diversity, soil organism manipulation, organic and mineral fertilization) allowing us to propose several indicators that has been and can be used in field experiment. At the end of this project, we can affirm that the combination of the two *a priori* and *a posteriori* approaches, to select functional groups of fertilizers, have statistical, ecological and agronomic significance. On the one hand, the constitution of the functional groups was constructed from rigorous statistical criteria and considers the interactions that actually occur between the fertilizer materials. On the other hand, the farmers' assessments were considered as soon as the protocol was set up, in particular on the dose, and the results from the combinatorial model offer a possibility of choosing high-performance assemblage with respect to which farmers can take into account their specific constraints.

*** WP3 outcomes**

Despite the limitations of the study, the conduct of two years of experimentation at Ivory and three years at Imerintsiatosika made it possible to identify several practices for restoring the ecological functions of soils which improve the agronomic and ecological performance of soils. The impacts and repercussions of WP3 are notably palpable through the results of WP4 (multi-criteria indicators of ecological, agronomic and socio-economic descriptors) and the results of WP5 (farmer assessment crossed with scientific indicators). **Farmers** were able to benefit from new knowledge through the evaluation of innovative SFRs proposed by scientists. On the other hand, the **scientists** were able to note that the capitalization of local knowledge remains important given the agronomic and ecological performance of the SFR17 proposed by the farmers. Co-construction between scientists and farmers is thus of fundamental importance for the scaling up of innovations.

*** WP4 outcomes**

The multicriteria indicator that was built in this project showed that it was able to finely discriminate the effect of agricultural practices on the functioning of an agroecosystem and their acceptability among **farmers**. This fineness of evaluation is due to the approach we followed to start from an exhaustive data set and to select the variables without *a priori* on the basis of their participation in the variance of the system, via high-performance and rapid statistical methods.

This indicator is intended for actors in the field such as **farmers**, **agricultural technicians**, **NGOs**, but also **researchers**. However, it is not intended to be used directly by non-scientific beneficiaries, for two reasons. The first is that it is based on precise scientific methods which require equipment, environment and scientific know-how. The fineness of the assessment we have obtained is partly due to the fact that the measurement techniques applied have not been 'degraded' with a view to being applied by non-scientists. The second reason is that the descriptors retained within a set of measured variables will be able to vary depending on the agricultural practices tested but also on the temporal evolution of the system. For example, soil carbon content is not a relevant descriptor after two years of organic input, but it will surely become so after 5 years. The passage from "variable" to "descriptor" therefore depends only on what the statistics tell us, and a good descriptor at year 2 will perhaps no longer be a good descriptor at year 5 and will generate inertia in the variation of the final indicator.

*** WP5 outcomes**

- With **farmers**: Thanks to two surveys addressed to all farmers part of the farmers' network, we were able to highlight early mechanisms about cross-learning linked to SECuRE activities with the farmers' network, such as flow of information, knew knowledge generation among farmers, change of perception about organic fertilizers, and willingness to change practices (Figure 1).

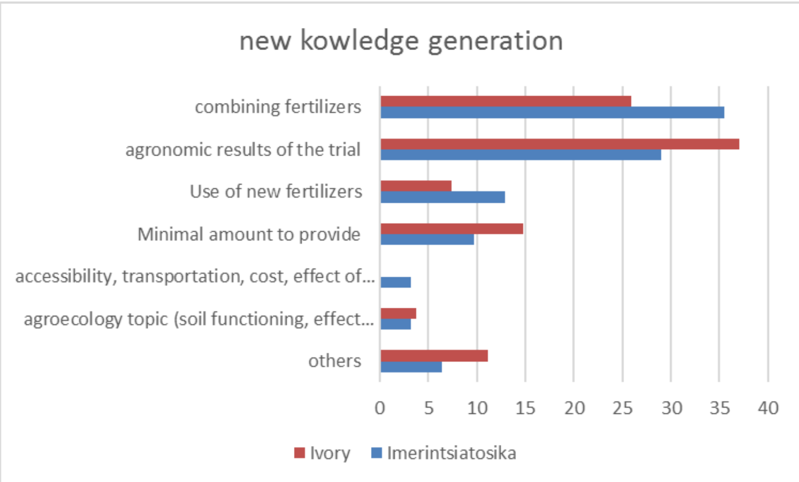

Figure 1: Generation of new knowledge by farmers after attendance SECuRE workshops

Farmers also declared that they are inclined to change their fertilization practices (38%) and 10% also declared that they already developed improved fertilization practices, and produced their own vermicompost, compost or liquid compost before attending SECuRE's workshop. Among those who want to improve their practices, 9 of them want to produce vermicompost or compost, 2 other want to increase the use of preserved manure or and 2 of NPK (Figure 2).

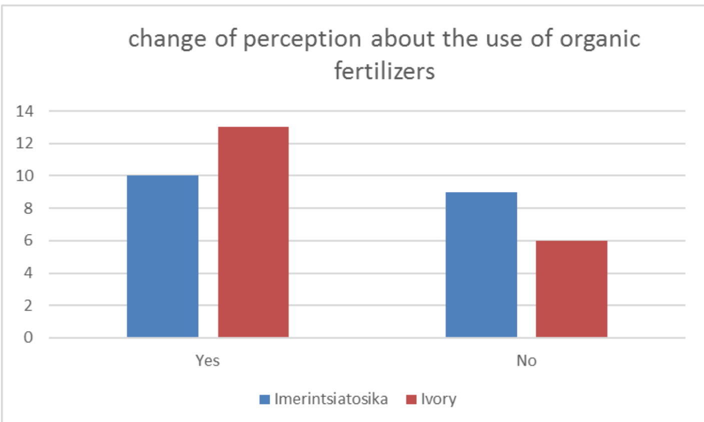

Figure 2: Change of perception by farmers about the use of organic fertilizers after attendance of SECuRE workshops

We also expect circulation of SECuRE's results and new knowledge thanks to intra-group discussion, but also extra-group discussion among neighbors or family networks; as 73% of farmers report having already discussed about

SECuRE results 15 days after the last workshop. Discussion targets pro and coins of several organic fertilizers and the results of the SECuRE's agronomic trial.

- With **advisory and extension services**, we identified issues to be investigated, respect to technical issues: like how to improve the quality of compost and vermicompost, or respect to development issues: how to engage farmers from the farmers' network into changes of practices and how to extend the circulation of knew knowledge among farmers. NGO Agrisud and GSDM technicians and supervisors took part to these discussions, and further development & research projects will target those aspects (for instance, MAKIS, DINAMICCS (UE Funded projects)).

- With **students**, we supervised 9 Master students (6 Malagasy et 3 French) and one PhD thesis (Manoa Raminoarison, defense in June 2021). A group of 5 students from Institut Agro Montpellier (*Projet d'Etudiants Ingénieurs*) developed pedagogical materials through 10 technical sheets on soil ecological indicators and a group of 7 students from ESSA Antananarivo realized 3 movies on the same soil ecological methods (available on the SECuRE website). Some students were also actively involved into the production of extension products: the booklet, the guide on household soil restoration practices, and practical sheets on fertilizers (**Erreur ! Source du renvoi introuvable.**).

Figure 1: Front pages of the guide on household soil restoration practices 36p (left), the fascicle with practical sheets on fertilizers, 14 sheets (right)

- With **scientific communities** we produced and disseminate our results in the form of 6 scientific publications in international journals, 4 publications in non-indexed journals, 2 chapters in FAO reports, 6 oral presentations and 2 posters in international conferences, 8 oral presentations in national conferences. Four other articles are finalized and about to be submitted in international journals. Other are in preparation.

- With **decision makers and large audience**, we
  - took part to several national and international conferences
  - organized a national workshop in Antananarivo in February 2021 on ecological intensification (feb 2021) and disseminated the guide on households and the practical sheets to 50 attendees from decision makers, scientists and practitioners);
  - upload documentations and movies on the SECuRE project website
  - upload scientific documentation on institutional partners' websites and data storage platforms (Agritrop for Cirad, Base Horizon IRD)
  - popularized certain results in the form of scientific news sheets (https://www.ird.fr/mobiliser-les-vers-de-terre-pour-ameliorer-les-productions-agricoles)
  - developed pedagogic tools for students: (a teaching lesson on the restoration of soil ecological restoration and a report in the 'Techniques de l'Ingénieur' (soon available online)

V. PERSPECTIVES

Different new research questions arose from the project, whether globally over the whole project or specifically within each WP.

*** WP1 perspectives**

These studies reveal the relevance in conducting multi-disciplinary approaches. Research needs to refine/strengthen studies on improved animal husbandry, including feeding, health or habitat, which can enhance the quantity and fertilizing quality of the fertilizers. The improvement can be extended to short-cycle animals such as poultry and/or pigs, and not only cattle, because this type of farming exists in all types of farms. It could also be interesting to carry out research on how to make zezi-pako production evolve towards a farm waste with more fertilizing qualities, considering the new issues on the availability of plant raw materials and the need for a technical-economic reference system.

The results showed that farmers use almost no inputs, neither organic nor inorganic, on irrigated lowland rice. Although, this crop is strategic for farmer (importance of the area, basis of food and food security, but also monetary income from marketed rice, etc.). Farmers are also aware about the potential gains in rice yield if they use fertilizers. It would then be interesting to analyze the technical and economic constraints on the use of fertilizers and other inputs on lowland rice by family farmers in rural areas under the assumption that the costs compared to the expected gains would be the main constraint.

*** WP2 perspectives**

We identified several new questions to address in the future to better assess the effect of innovative fertilization management plans, including soil organisms' inoculation or management.

1. What about the dose in the diversity effect of fertilizers? An important agronomic factor which was not well tested, is the fertilizer dose. The dose should vary depending on the class of material, which can be either an organic amendment or a mineral fertilizer. The dose calibration of the studies conducted in the WP2 using the combinatorial approach was different. For the controlled greenhouse test, the individual mass of materials was kept regardless of the assemblies, considering that the assigned dose is a character in itself of the material. The doses provided were based on *a priori* knowledge according to which the fertilizers were provided by the farmers. For the field trial, the dose was set by taking the farmer doses as a reference, and was calibrated on the same total mass. Because the content of nutrients varies considerably between materials, the situations between fertilizing materials in assembly and supplied alone, also vary greatly. Thus, the method of calibrating the dose is the methodological obstacle that remains and may constitute the main limitation of our study. At last, the question of the availability of raw materials to produce organic fertilizers is still important.

2. What about the long-term effects of material assemblages? In this study, our interpretations were limited to the analysis of the effects of assemblages on soil fertility at the scale of the crop year. The fertilizer classification in the functional groups is therefore interesting for rapid crop production, which is in line with the urgency of production of family food crops, but does not provide a generic framework over medium or long times. Other materials such as zebu horn, dolomite and phosphate rock require relatively long years for their effects (mineralization, release of nutrients) to be expressed. It would be interesting to extend the duration of the experiment over several crop cycles in order to determine the potential effects of the materials (for information, we plan to continue the trial over the next three years).

3. Contaminant or pollutant effects of assemblies of materials. The environmental issue concerning the use of fertilizers has gained momentum in subjects dealing with the valuation of mainly organic products. Risks include greenhouse gas emissions and the accumulation of trace metal elements in the soil. Fertilizers from urban waste are

the most discussed. It would be interesting to take these aspects into account and to study the performance of the assemblies in relation to these parameters. It would also provide answers if the interaction between the parameters reduces the contamination of plants and accelerates the elimination of these pollutants from soils.

4. Relationship between the characteristics of fertilizers and the groups of materials formed. This study has shown that the performance of the fertilizer assemblages is mainly under the effect of composition. As the selected materials were characterized before the experiment, the amounts of nutrients provided in each assemblage were known. One study which could be carried out could consist in carrying out a statistical analysis on the relation between the intrinsic qualities of the materials and the responses of the assemblages. More precisely, the idea is to test a model to explore which characteristics of the materials explain the functional group composition.

5. Testing K and micronutrients. Further research focusing on K, Mo and other micronutrients such as Zn should be conducted to more fully characterize the upland rice nutrient limitations of Ferralsols from Madagascar. In the current need to promote agroecological practices, the restoration of the soil fertility by the application of both mineral and organic fertilizers, providing available P, Ca, N and Mg in sufficient amounts and by the correction of pH acidity, are required to sustain the production of smallholder farms in the Highlands.

6. Increase our knowledge on the effects of soil biodiversity not only on soil and plant parameters, but also on soil/crop resilience to climate change and events, and on the nutritional quality of crop products for health issues.

*** WP3 perspectives**

The field trial set up at Imerintsiatosika and followed for 4 years now has made it possible to discriminate very interesting pedo-agronomic situations which deserve to be studied in the longer term, in particular with the objective of understanding the links between fertilization, soil ecological functions and agricultural production. This experimental device has already attracted new projects, particularly with the objective to understand the link between soil functioning and climate resilience. In the MOGPA (Make Our Planet Great Again) project (associated with funding a post-doc scholarship for our colleague Onja Ratsiatosika), started in October 2020, the objective is to identify the practices that give upland rice the best resilience in the face of reduced rainfall. A rain exclusion device was installed on two “peasant” SFRs (SFR17, SFR3) and three "scientific" SFRs (SFR18, SFR19, SFR24). The other SFRs (20 treatments) were rotated with a voandzou (or ground peas) crop. In the next growing season (2021-2022), the DINAAMICC (DESIRA, UE) project will continue the rain exclusion trial and the ANR U2Worm project will focus on the effect of earthworm inoculation on the stabilization of organic matter with a view of 4p1000 initiative.

*** WP5 perspectives**

The project outputs and outcomes generated raise issues about multicriteria assessment, trade-offs between several stakeholders having different perspectives, values, knowledge and affordances.

It also questions about support scaling mechanisms: as many famers declare being interesting in changing practices (like producing their own vermicompost and compost), they also raised numerous blockages that hinder substantial changes in farming practices (like lack of cash to start new cropping activity, lack of evidence about climatic risks, etc.). This highlights the mechanisms to support and develop an ecosystem of relevant and timely support services providers able to support such complex changes encompassing several types of services: advisory services, access to equipment, credit, information, institutional support and access to market, capacity building, etc. To start with, we suggest pursuing to support co-learning about organic fertilization but involving other types of stakeholders so that the scale of the agricultural innovation system will be addressed.

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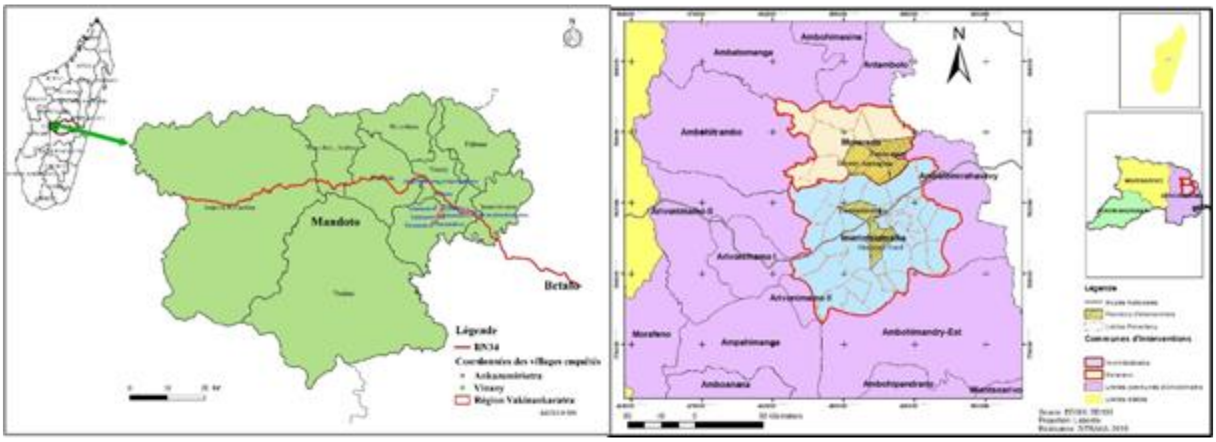
APPENDIX

SECURE

Appendix 1: Location of the two study areas: the West of the region of Vakinankaratra (District of Mandoto, called 'Ivory' in the project) on the left, and the East of the region of Itasy (District of Arivonimamo, called 'Imerintsiatosika' in the project) on the right



Appendix 2: Distribution of the samples by municipality

Municipality	Fokontany	Estimated population	Number of households	Number of surveyed households	Sampling rate	Coefficient of Extrapolation
Ankazomiriotra	Tatamolava	2 809	562	48	8,5%	11,71
	Andratsaimahamasina	1 013	203	35	17,2%	5,80
Vinany	Mazoto	1 232	246	35	14,2%	7,03
	Ampasatokana	2 000	400	34	8,5%	11,76
ST District of Mandoto (Ivory)		7 054	1 411	152	10,8%	
Morarano	Fenomanana	1 516	339	45	13,3%	7,53
	Sabotsy	3 700	828	42	5,1%	19,71
Imeritsiatosika	Morarano Nord	2 110	416	42	10,1%	9,90
	Tsenamasoandro	3 200	631	42	6,7%	15,02
ST District of Arivonimamo (Imerintsiatosika)		10 526	2 214	171	6,7%	
All sample		17 580	3 625	323	7,7%	

Appendix 3: Description and origin of 19 organic and mineral fertilizers available in the Highlands of Madagascar

Code	Class	Type	Norms	Description	Manufacturer
AshE	Fertilizers	Vegetable ashes	NF U42-001	**Ash** derived from combustion of *Eucalyptus* branches	Itasy farmer
AshH	Fertilizers	Vegetable ashes		**Rice husk ash** obtained after burning out the husk in air	Itasy farmer
AshS	Binary PK fertilizers (Class II)	Vegetable ashes		**Rice straw ash** obtained after straw open-field burning	Vakinankaratra farmer
ComL	Organic amendments	Vegetable and animal composts	NF U44-051	**Compost** of mixing of: rice straw. *Helianthus. Aristida sp.*.and farmyard manure (Man_I product)	Laboratory of Radio Isotopes
VCL	Organic amendments	Vegetable and animal composts	NF U44-051	**Vermicompost** of mixing of: rice straw. *Helianthus.Aristida sp.* and farmyard manure (Man_I product). indigenous earthworm species: *Eudrilus eugeniae*	Laboratory of Radio Isotopes
VCT	Organic amendments	Vegetable and animal composts	NF U44-051	**Vermicompost** of mixing of: farmyard manure and disposal vegetables. imported earthworm species: *Eisenia foetida*	TATA association
VCV	Organic amendments	Vegetable and animal composts	NF U44-051	**Vermicompost** of mixing of: farmyard manure. soil. rice straw and legumes (mainly *Melia azedarac*). imported earthworm species: *Eisenia foetida* and *Eisenia andrei*	Vakinankaratra farmer
Tar	Organic amendments	Vegetable and animal composts		**Bacterial leaven** fixed on a rich organic plant support, certified organic by Ecocert. commercially known as Taroka Phosphaté	STOI Agri Company
ComM	Organic amendments	Household fermentable composts	NF U44-051	**Fermentable composts** from the dumpsite of Mahajanga municipal solid waste landfill under natural composting	Madacompost company
ComT	Organic amendments	Household fermentable composts		**Fermentable composts** from the dumpsite of Andralanitra municipal solid waste landfill under natural composting	AKAMASOA Association
ManI	Organic amendments	Manures	NF U44-051	Fermentation of raw **cattle dejections** (excrements + urine) collected over vegetable residues mainly constituted of rice straw and prepared in outside rudimentary park	Itasy farmer
ManV1	Organic amendments	Manures	NF U44-051	Fermentation of raw **cattle dejections** (excrements + urine) collected over vegetable residues mainly constituted of rice straw. The product is prepared and stored in closed place and collected in a specific recipient	Vakinankaratra farmer
ManV2	Organic amendments	Manures	NF U44-051	Fermentation of raw **cattle dejections** (excrements + urine) collected over vegetable residues mainly constituted of rice straw and prepared in outside rudimentary park	Vakinankaratra farmer
PP	Organic amendments	Animal dejections without residues	NF U44-051	**Non-fermentable mixing of soil and cattle dejection (park powder)** collected in outdoor park and stored in the open air	Vakinankaratra farmer
DroG	Entirely animal-based NP fertilizer (Class VI)	Bat guano droppings	NF U42-001	**Dried droppings of bats (guano)**. Product formed by accumulation and aging of those dropping birds. cave in the Southeast Region	Guanomad company
DroP	Entirely animal-based NP fertilizer (Class VI)	Dried poultry droppings	NF U42-001	Desiccated product obtained by the accumulation and drying of **poultry excrement** for the production of commercial broilers	Itasy farmer
ZH	Nitrogen organic fertilizer (classe V)	Crushed zebu horn	NF U42-001	Product obtained by **crushing and grinding zebu horns** of different diameters: flour. semolina. shavings	Madacompost company
Dol	Fertilizer providing Ca. Mg. Na and/ or S (Class III)	Dolomite	NF U42-001	Natural product essentially containing double carbonate of Ca and Mg. deposit in Ibity. Vakinankaratra Region	SEPCM Companies
Hyp	Phosphorus fertilizer	Rock phosphate + Volcanic black soil		Organo-mineral product obtained from mixing micronised apatitic rock and volcanic black soil, known commercially as **Hyperfos**	Prochimad Company

Appendix 4: List of SFR tested in the field trial

In year 1 (2017-2018), sixteen SFR treatments were tested for the two sites (Itasy and Ivory):

*** Two control practices:**

- **SFR8** "adequate" mineral fertilization (100 kg/ha NPK and 100 kg/ha urea in two applications)
- **SFR16** without any fertilization

*** Three peasant practices:**

- **SFR1** parkland powder (3 t DM/ha)
- **SFR2** traditional manure (3 t DM/ha)
- **SFR3** traditional manure (3 t DM/ha) + mineral fertilization (40 kg / ha NPK)

*** Eleven "scientific" practices (innovations):**

- four organic materials processed alone:
  - (i) **SFR4** traditional manure (6 t DM/ha)
  - (ii) **SFR5** improved manure (6 t DM/ha)
  - (iii) **SFR6** compost (6 t DM/ha)
  - (iv) **SFR7** vermicompost (6 t DM/ha)
- three assemblages of organic and mineral matter:
  - (i) **SFR9** traditional manure (6 t DM/ha) + dolomite (500 kg/ha)
  - (ii) **SFR10** traditional manure (6 t DM/ha) + ash (500 kg/ha)
  - (iii) **SFR11** traditional manure (6 t DM/ha) + prochimad (500 kg/ha)
- a mixture of organic matter:
  - (i) **SFR12** traditional manure (2 t DM / ha) + compost (2 t DM/ha) + vermicompost (2 t DM/ha)
- three assemblages of mixed organic matter and mineral matter:
  - (i) **SFR13** = SFR12 + ash (500 kg/ha)
  - (ii) **SFR14** = SFR12 + prochimad (500 kg/ha)
  - (iii) **SFR15** = SFR12 + guanomad (500 kg/ha).

In year 2 (2018-2019), the SFR practices from year 1 were renewed, then new practices were added, including nine SFR for the Itasy site and six SFR for the Ivory site.

* Three new "scientific" practices:

- two practices with high inputs:
  - (i) **SFR18** processed organic matter alone (traditional manure at 18 t DM/ha)
  - (ii) **SFR19** mixture of several processed organic materials (traditional manure (6 t DM/ha) + compost (6 t DM/ha) + vermicompost (6 t DM/ha)
- **SFR20** traditional manure (6 t DM/ha) added in 3 installments (each month).

* A new control treatment

- **SFR21** identical to SFR 8

* Five new practices specific to Itasy

- **SFR17** a peasant practice: pig slurry (3 t DM/ha) + ash (500 kg/ha)
- four "scientific" practices:
  - (i) **SFR22** traditional manure (18 t DM/ha) applied in mulch
  - (ii) **SFR23** traditional manure (6 t DM/ha) + crab meal (500 kg/ha)
  - (iii) **SFR24** = SFR12 + poultry manure (500 kg/ha)
  - (iv) **SFR25** mixture fertilizers applied in layers: traditional manure (2 t DM/ha) + vermicompost (2 t DM/ha) + compost (2 t DM/ha).

* Two new practices specific to Ivory

- two peasant practices:
  - (i) **SFR17 Ivory** traditional manure (1.5 t DM/ha) + improved manure (1.5 t DM/ha)

(ii) **SFR26 Ivory** traditional manure (3 t DM/ha) + ash from rice straw (500 kg/ha).

In year 2 (2018-2019), 11 SFR were inoculated with earthworms (at a density of 50 worms/m²) and mycorrhizae, simultaneously, in order to test the effect of habitat restoration. The treatments inoculated were: SFR4, SFR5, SFR6, SFR7, SFR9, SFR10, SFR11, SFR12, SFR13, SFR14 and SFR15.

The following table summarizes the codes and constituent materials of the SFRs :

N° SFR	CONSTITUANTS
SFR1	Park powder (3 t DM /ha)
SFR 2	Traditional manure (3 t DM/ha)
SFR 3	Traditional manure (3 t DM/ha) + NPK (40 kg/ha)
SFR 4	Traditional manure (6 t DM/ha)
SFR 5	Improved manure (6 t DM/ha)
SFR 6	Compost (6 t DM/ha)
SFR 7	Vermicompost (6 t DM/ha)
SFR 8	Mineral fertilization (NPK 100 kg/ha + urea 100 kg/ha)
SFR9	Traditional manure (6 t DM/ha) + dolomite (500 kg/ha)
SFR10	Traditional manure (6 t DM/ha) + rice husk ash (500 kg/ha)
SFR11	Traditional manure (6 t DM/ha) + prochimad (500 kg/ha)
SFR12	Traditional manure + compost + Vermicompost à 2 t DM/ha each
SFR13	= SFR12 + ashes (500 kg/ha)
SFR14	= SFR12 + superphosphate (500 kg/ha)
SFR15	= SFR12 + guano (500 kg/ha)
SFR16	No inputs
SFR17 Itasy	Pig manure (3 t DM/ha) + rice husk ash (500 kg/ha)
SFR17 Ivory	Traditional manure (1.5 t DM/ha) + Improved manure (1.5 t DM/ha)
SFR18	Traditional manure (18 t DM/ha)
SFR19	Traditional manure + compost + Vermicompost at 6 t DM/ha each
SFR20	Traditional manure (6 t DM/ha) in three times
SFR21	Mineral fertilization (100 kg NPK/ha + 100 kg urea/ha)
SFR22 Itasy	Traditional manure (18 t DM/ha) in mulch
SFR22 Ivory	Traditional manure (6 t DM/ha) + rice straw ash (500 kg/ha)
SFR23	Traditional manure (6 t DM/ha) + crab meal (500 kg/ha)
SFR24	= SFR12 + chicken manure (500 kg/ha)
SFR25	Traditional manure + compost + lombricompost at 2 t DM/ha chacun, in layers

In year 3 (2019-2020), the test was only carried out on the Itasy site. All of the twenty-five practices tested in year 2 (2018-2019) were repeated. As the inoculation of earthworms and mycorrhizae was only carried out in year 2 (2018-2019), the trials in year 3 mainly focused on the organic and mineral inputs appropriate to each LICO.

Appendix 5: List of soil and plant analyses

A large number of measurements were made on soil and plants. The different measures are as follows:

- Characterization of fertilizers (15 parameters): total C, N, P, S, K, Ca, Mg contents, C/N, C/P, C/S, C/K, C/Ca, C/Mg, van Soest analysis (hemicellulose, cellulose, lignin)

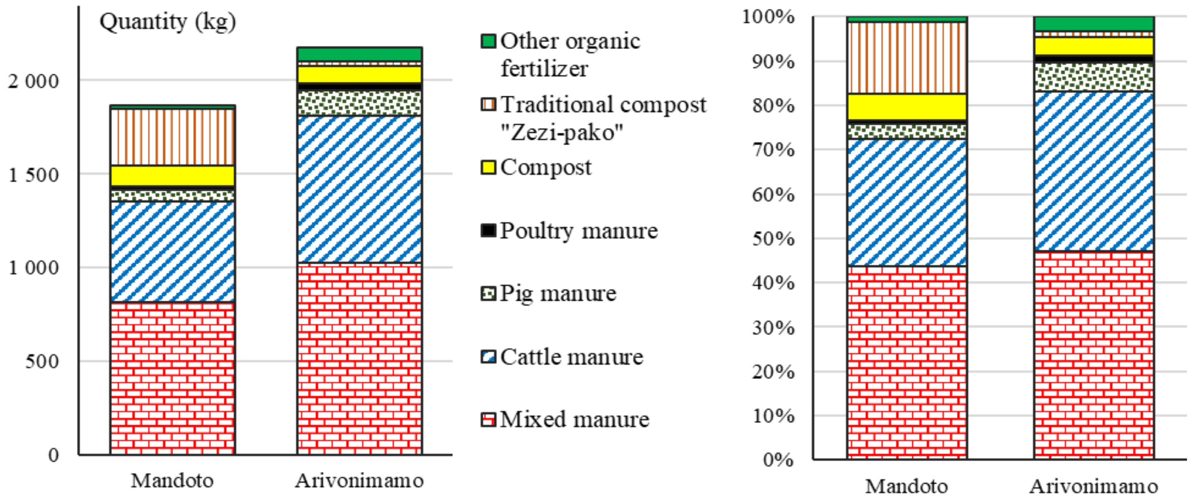
- Agronomic descriptors (60 parameters):

- plant height: height after 1 month, height after 2 months
- plant biomass: shoot and root biomass, shoot:root ratio, height after 3 months,
- Cop yield: yield components (height, number and weigh of stalks, number and weigh of panicles, number of tillers, weigh of grains, grain yield, straw yield, harvest index, % of filled grains
- Grain quality: carbon, nitrogen and phosphorus content, C/N ratio
- Straw quality: carbon, nitrogen and phosphorus content, C/N ratio, dry matter, evaluation by infrared spectrometry (total ashes, N content, cellulose, neutral detergent fiber, acid detergent fiber, acid detergent lignin), SPAD

- Soil ecological descriptors (92 parameters):

- maintenance of a good physico-chemical environment: pH in situ, pH_{eau} laboratory, soil water content (0-10 and 10-20 cm), bulk density (0-10 and 10-20 cm), soil macroaggregation (0-10 and 10-20 cm), biomass of soil engineers
- carbon dynamics: total soil carbon content (0-10 cm), soil carbon stock (0-10 cm), PoxC (0-10 cm), soil respiration (3, 7, 15, 21, 28 days, kinetic and cumulative), tea bag decomposition (green tea and rooibos, 3 months), bait lamina decomposition (21 days), Ecoplates substrate decomposition (total AWCD, AWCD for carbohydrates, AWCD for polymers, AWCD for carboxylic acids and cetones), biomass of soil detritivores
- nutrient cycling: total N content and stock (0-10cm), exchangeable resin P content and stock (0-10 cm), microbial P content (0-10 cm), density of fungivore, omnivore and carnivore nematodes, nematode channel ratio, Ecoplates substrate decomposition (AWCD for amines and amides, AWCD for aminoacids)
- maintenance of a good level of biodiversity: Soil macrofauna from TSBF monoliths (taxa richness, biomass and density of total macrofauna, earthworms, detritivores, ants, engineers, omnivores, phytophagous), soil macrofauna in pitfall traps (biomass of macrofauna, diversity, taxa richness), soil nematofauna (abundance, total density, density of omnivores, carnivores, bacterivores, fungivores, taxa richness, enrichment index, structure index, maturity index, phytoparasites index)
- regulations of pathogens: biomass and density of soil pests (mainly white grubs), phytoparasite nematodes (maturity index, phytoparasite index, density of phytoparasites, structure index)

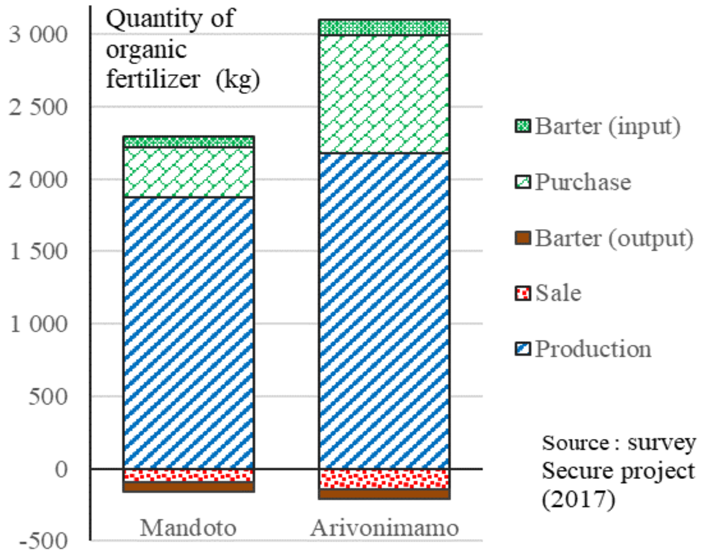
Appendix 6: Composition of the average amount of fertilizers produced per farmer in each region



Appendix 7: main products brought in to make manure or farm wastes (as % of farmers)

Raw material	Manure (farmers=304)	Farm waste (farmers=122)
Cattle manure	70%	60%
Pig manure	73%	
Poultry manure	84%	
Other manure	1%	
Rice straw	72%	60%
Rice husks	51%	33%
Other crop residues	43%	39%
Bozaka	68%	60%
Other "grasses	17%	9%
Tree leaves	13%	50%
Household waste	36%	54%
Ash	46%	57%
Fertile soil / Potting soil	3%	12%
Salt	4%	9%
Worms	0%	2%
Other products	4%	7%

Appendix 8: Input and output of organic fertilizer at farm level



Appendix 9: Organic and inorganic fertilizer inputs on pure crops in Mandoto

Pure crop	Number of plot	Area (ha)	% plot with fertilizer		% area with fertilizer		Average application rate of organic fertiliser (kg/ha)*		Average application rate of inorganic fertiliser (kg/ha)*	
			organic	inorganic	organic	inorganic	All plots	Plot with fertiliser	All plots	Plot with fertiliser
Rice in lowland	242	58.3	20%	4%	18%	4%	377	1 901	2.41	58.25
Rice in upland	90	23.5	91%	37%	90%	29%	4 022	4 415	10.11	26.77
Maize	30	6.4	97%	37%	98%	43%	3 923	4 059	16.69	45.53
Cassava	117	36.9	8%	0%	4%	0%	414	4 843	0.00	0.00
Other tubers	19	2.3	47%	47%	35%	42%	3 041	6 420	18.57	39.20
Legumes	78	11.5	45%	18%	38%	18%	1 776	3 958	8.70	48.50
Vegetables	112	2.6	90%	61%	80%	74%	31 829	35 296		

* estimates calculated per plot without weighting

Appendix 10: Organic and inorganic fertilizer inputs on pure crops in Arivonimamo

Pure crop	Number of plot	Area (ha)	% plot with fertilizer		% area with fertilizer		Average application rate of organic fertiliser (kg/ha)*		Average application rate of inorganic fertiliser (kg/ha)*	
			organic	inorganic	organic	inorganic	All plots	Plot with fertiliser	All plots	Plot with fertiliser
Lowland rice	363	60.8	39%	9%	39%	8%	633	1 643	4.59	52.06
Upland rice	72	10.5	83%	0%	93%	0%	2 902	3 482	0.00	0.00
Maize	17	1.1	94%	11%	96%	9%	3 501	3 720	1.31	22.22
Cassava	201	20.2	24%	1%	23%	0%	1 253	5 249	0.38	38.33
Other tubers	232	23.3	70%	5%	78%	4%	4 461	6 350	3.67	77.48
Beans	61	7.6	95%	65%	96%	73%	4 132	4 346	48.24	75.45
Other legumes	46	3.5	20%	0%	18%	0%	779	3 981	0.00	0.00
Tomatoes	90	9.5	97%	95%	98%	97%	7 614	7 877	127.91	135.43
Green beans	132	10.9	95%	87%	96%	90%	5 079	5 321	80.90	92.86
Other vegetables	155	12.9	95%	76%	101%	73%	4 311	4 546	91.26	120.89

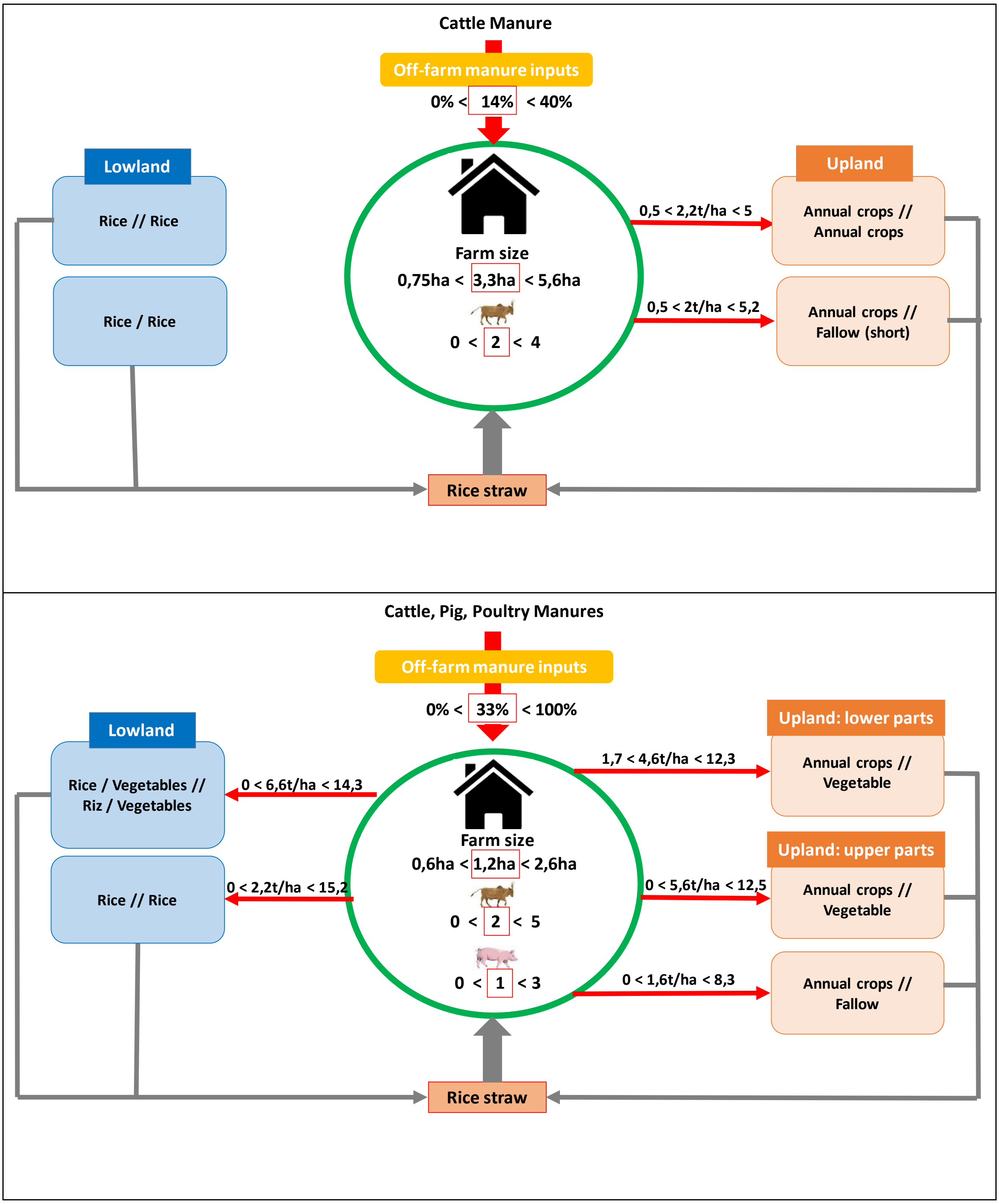
* estimates calculated per plot without weighting

Appendix 11: Organic and inorganic fertilizer input on the most associated crops in Arivonimamo

Districts	Number of plot	Area (ha)	% plot with fertilizer		Average application rate of organic fertiliser (kg/ha)*		Average application rate of inorganic fertiliser (kg/ha)*	
Mandoto			organic		All plots	Plot with fertiliser	All plots	Plot with fertiliser
Upland rice + Maize	114	25.77	91%	32%	656	719	2.6	8.3
Maize + Cassava	50	11.49	88%	2%	420	477	0.1	3.0
Maize + Legumes	57	9.75	84%	16%	428	508	0.2	1.5
Maize + Cassava + Legumes	24	4.82	75%	13%	242	323	0.2	1.8
Cassava + Legumes	24	5.87	4%	0%	11	250	0.0	0.0
Arivonimamo								
Upland rice + Maize	14	1.82	86%	0%	366	427	0.0	0.0
Maize + Legumes	25	2.28	84%	24%	188	224	1.5	6.2
Cassava + Legumes	13	1.26	54%	0%	280	521	0.0	0.0
Tubers + Fruit tree	34	2.70	62%	12%	224	363	0.3	2.8
Other crops. + Fruit tree	90	6.71	91%	52%	5 414	255	3.0	5.8

* estimates calculated per plot without weighting

Appendix 12: Resource map flows synthesis at the farm level for each cropping system during the 2017-2018 cropping season in Vakinankaratra (up) and Itasy (down)



Appendix 13: Organic manures in terms of soil enrichment (organic matter, acidity), crop nutrition (nitrogen, phosphorus), and rice yields obtained during the 2017-2018 cropping season in Ivory (up) and Imerintsiatosika (down)

Organic Manure	Soil enrichment		Crop nutrition		Rice production
	Organic matter (%)	Acidity (unit)	Nitrogen (%)	Phosphorus (mg kg^{-1})	Paddy (t^{-1})
Farm waste	13	8.5	0.4	0.1	2.9
Cattle based	30	9.4	1.0	0.2	1.0
	17	8.5	0.6	0.4	3.0
	18	7.5	0.7	0.3	2.9
	35	8.9	1.3	0.3	1.9
	30	9.0	1.3	0.3	2.7
	24	8.4	0.9	0.5	2.9
	35	8.1	1.4	0.3	2.2
	32	8.9	1.2	0.3	3.0
	23	9.6	0.9	0.4	2.3
	16	8.0	0.6	0.3	2.4
	46	9.6	2.1	0.4	2.4
	21	8.4	0.7	0.5	1.5
	26	9.3	1.1	0.3	2.7
Improved cattle	32	9.0	1.5	0.7	3.1
	40	9.6	1.7	0.3	3.3
	25	9.3	1.1	0.3	2.9
Mixed cattle and pig	42	8.9	1.6	0.3	2.9
Compost	26	6.9	1.2	0.4	2.5
Vermicompost	32	6.9	1.3	0.3	3.4

Organic Manure	Soil enrichment		Crop nutrition		Rice production
	Organic matter (%)	Acidity (unit)	Nitrogen (%)	Phosphorus (mg kg^{-1})	Paddy (t^{-1})
Cattle based	38	7.3	1.6	1.9	4.7
	59	8.2	1.4	0.4	
Pig based	41	6.2	1.4	0.9	5.9
Mixed cattle and poultry	37	7.3	1.1	0.4	
Mixed cattle and ashes	24	8.9	0.7	0.3	5.5
	26	8.2	0.8	0.5	
	22	8.9	0.9	0.6	6.9
	6	9.3	0.2	0.2	1.7
	7	9.0	0.3	0.3	5.5
Mixed pig and ashes	23	7.5	0.7	0.5	
Mixed cattle, porc and ashes	38	8.7	1.0	0.3	2.5
	24	9.2	0.9	0.5	2.4
	28	7.7	1.3	1.6	5.0
	36	7.0	1.6	1.5	4.2
	23	7.6	1.0	0.8	3.1
	7	8.8	0.4	0.5	
Mixed cattle, poultry and ashes	17	9.0	0.5	0.3	4.9
Mixed cattle, poultry and pig	20	8.6	0.7	0.4	3.7
	24	8.1	0.9	0.4	7.8
	44	8.0	2.0	1.7	5.2

Appendix 14: Farmers' scoring of organic manures on social, economic and agronomical criteria compared with the fertilizer control (NPK 11-22-16)

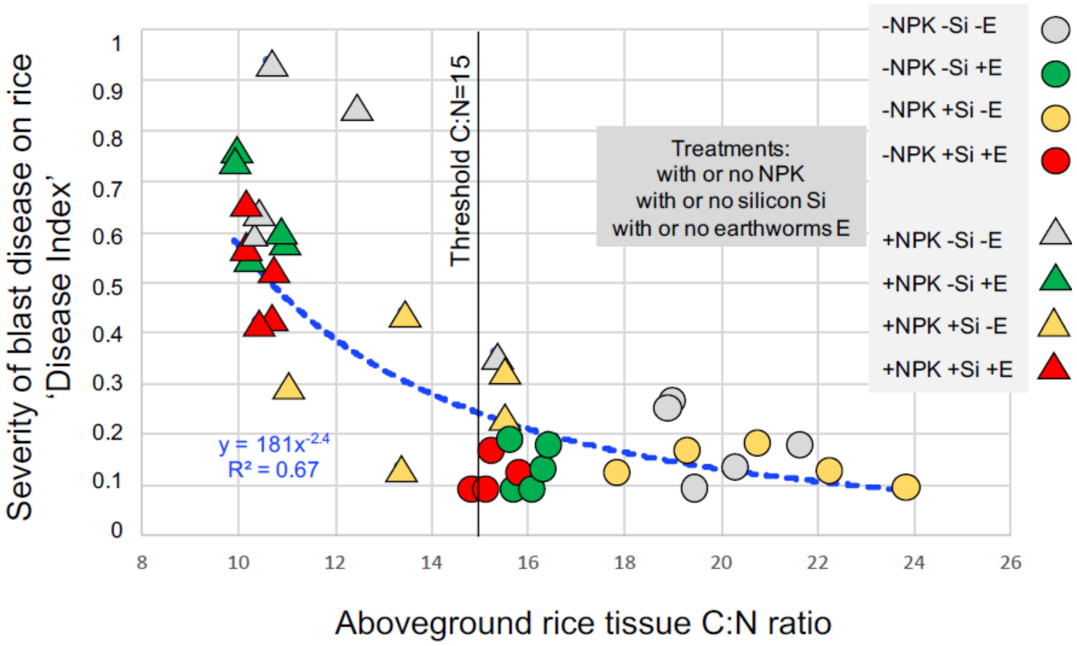
Fertiliser and Organic manure scoring			
Very Good	Good	Low	Very low

Fertiliser and Organic manure type	Farmers' criteria							
	Social and economical				Agronomical			
	Cost	Access	Field handling	Transport	Soil	Multi-use	Weeds and pests	Rice yield
NPK 11-22-16	Very low	Very Good	Very Good	Very Good	Very low	Good	Very Good	Low
Cattle based	Very Good	Very Good	Good	Good	Very Good	Good	Low	Low
Improved Cattle	Good	Good	Good	Good	Very Good	Very Good	Good	Good
Cattle and soil based	Very Good	Very Good	Very Good	Very Good	Very Good	Good	Low	Low
Lombricompost	Very low	Very low	Very Good	Very Good	Very Good	Very Good	Very Good	Good
Compost	Low	Low	Very Good	Very Good	Very Good	Very Good	Very Good	Good

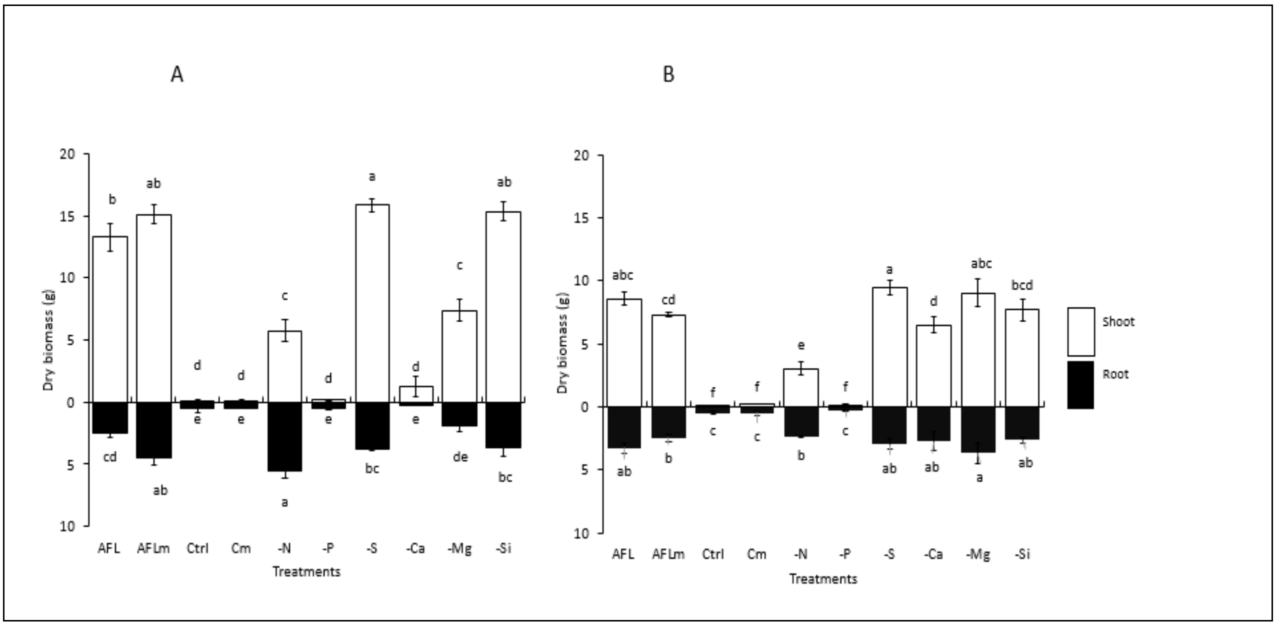
Appendix 15: Main characteristics of the Malagasy soils used in the experiment

Soil parameters	Units	Sites	
		Imerintsiatosika IM	**Ivory IV**
Elements			
Total C	g kg^{-1}	29.2	15.2
Total N	g kg^{-1}	2.07	1.53
Total P	g kg^{-1}	1.43	0.38
Total S	g. kg^{-1}	0.3	0.3 4
pH_{water}		4.70	4.83
pH_{KCl}		4.09	4.10
CEC	$cmol^{+}$ kg^{-1}	1.73	1.49
Exch. Ca	$cmol^{+}$ kg^{-1}	0.42	0.53
Exch. K	$cmol^{+}$ kg^{-1}	0.06	0.08
Exch. Mg	$cmol^{+}$ kg^{-1}	0.15	0.16
Exch. Al	$cmol^{+}$ kg^{-1}	0.59	0.77
P Olsen	mg kg^{-1}	3.76	3.86
P resin	mg kg^{-1}	0.47	1.15
Pi_NaOH	mg kg^{-1}	53.60	27.23
P total_NaoH	mg kg^{-1}	196.90	96.10
P_NaOH [a]	mg kg^{-1}	143.33	68.87
Particle-size distribution			
Clay + fine silt	%	71.3	45.6
Coarse silt	%	15.3	3.9
Fine sand	%	8.6	11.4
Coarse sand	%	4.6	38.7
Oxides			
Total Fe_2O_3	%	31.43	12.2
Total Al_2O_3	%	28.13	32.4
Total SiO_2	%	10.0	39.0
Total TiO_2	%	6.0	1.5
Total MgO	%	0.08	0.11
Total P_2O_5	%	0.30	0.13
Total MnO	%	0.08	0.15
Total K_2O	%	0.04	0.13
Total CaO	%	0.02	0.07
Others	%	0.29	0.20
Mineral contents			
Kaolinite	mg kg^{-1}	112.48	431.34
Gibbsite	mg kg^{-1}	201.26	161.18
Fe_2O_3_cbd	mg kg^{-1}	29.10	45.63

Appendix 16: Disease Index (DI) as a function of aboveground tissues C:N ratio using a power y~a*x^b function (R^2 = 0.67, a = 181, b = -2.4, 'nls' function from "stats" package)



Appendix 17: Final shoot (white bars) and root (black bars) dry biomass for (A) Chhomrong Dhan and (B) Nerica 4 rice cultivars grown in acidic ferrallitic soils from Imerintsiatosika and Ivory, respectively. Vertical bars represent standard deviations. Significant differences between the treatments at the 5% threshold are indicated with the different letters (a, b, c, d, and e) according to one-way ANOVA, followed by a post hoc Tukey HSD test.



Appendix 18: Ranking of SFRs in relation to biomass production in year 1 (2017-2018) on the Ivory site

Rang	**SFR**	**Biomasse totale (t MS/ha)**	**SFR**	**Grains (t MS/ha)**
1	SFR 5	2.41	SFR 5	1.16
2	SFR 15	2.13	SFR 15	0.97
3	SFR 14	2.10	SFR 14	0.94
4	SFR 7	2.06	SFR 7	0.91
5	SFR 8	2.01	SFR 8	0.86
6	SFR 13	1.86	SFR 13	0.80
7	SFR 6	1.67	SFR 3	0.71
8	SFR 3	1.66	SFR 6	0.69
9	SFR 12	1.51	SFR 12	0.63
10	SFR 10	1.31	SFR 10	0.57
11	SFR 9	1.26	SFR 9	0.55
12	SFR 1	1.19	SFR 1	0.48
13	SFR 4	1.17	SFR 11	0.47
14	SFR 11	1.13	SFR 4	0.45
15	SFR 16	0.86	SFR 2	0.35
16	SFR 2	0.78	SFR 16	0.32

The cells highlighted in yellow are the SFRs whose total biomass is greater than 2.00 t DM/ha

Appendix 19: Ranking of SFRs in relation to biomass production in year 2 (2018-2019) on the Ivory site

Rang	**SFR**	**Biomasse totale (t MS/ha)**	**SFR**	**Grains (t MS/ha)**
1	SFR5	9.97	SFR5	5.10
2	SFR19	7.47	SFR19	3.32
3	SFR6	6.97	SFR6	3.19
4	SFR14	6.64	SFR14	3.07
5	SFR12	6.55	SFR13	3.02
6	SFR13	6.35	SFR12	3.00
7	SFR15	6.26	SFR15	2.39
8	SFR7	5.86	SFR7	2.38
9	SFR9	5.18	SFR10	2.23
10	SFR10	5.04	SFR9	1.97
11	SFR8	4.76	SFR8	1.77
12	SRF11	4.22	SFR21	1.63
13	SFR21	3.85	SFR18	1.62
14	SFR18	3.51	SFR11	1.61
15	SFR4	3.28	SFR4	1.43
16	SFR17	3.02	SFR17	1.29
17	SFR3	2.92	SFR3	1.22
18	SFR1	2.71	SFR1	1.11
19	SFR16	2.10	SFR16	1.05
20	SFR2	2.04	SFR22	0.86
21	SFR22	2.03	SFR2	0.78
22	SFR20	1.72	SFR20	0.74

The cells highlighted in yellow are the SFRs whose total biomass is greater than 5.00 t DM/ha

Appendix 20: Ranking of SFRs in relation to biomass production in year 1 (2017-2018) on the Itasy site

Rang	SFR	Biomasse totale (t MS/ha)	SFR	Grains (t MS/ha)
1	SFR7	2.73	SFR7	1.14
2	SFR15	2.34	SFR15	1.08
3	SFR13	1.90	SFR5	0.92
4	SFR5	1.85	SFR14	0.91
5	SFR14	1.85	SFR13	0.89
6	SFR12	1.75	SFR12	0.83
7	SFR3	1.59	SFR4	0.72
8	SFR6	1.51	SFR6	0.71
9	SFR4	1.50	SFR3	0.69
10	SFR1	1.42	SFR1	0.67
11	SFR8	1.28	SFR9	0.61
12	SFR10	1.27	SFR11	0.58
13	SFR11	1.22	SFR8	0.56
14	SFR9	1.22	SFR10	0.51
15	SFR2	1.04	SFR2	0.51
16	SFR16	0.08	SFR16	0.00

The cells highlighted in yellow are the SFRs whose total biomass is greater than 2.00 t DM/ha

Appendix 21: Ranking of SFRs in relation to biomass production in year 2 (2018-2019) on the Itasy site

Rang	**SFR**	**Biomasse totale (t MS/ha)**	**SFR**	**Grains (t MS/ha)**
1	SFR19	5.74	SFR4	2.60
2	SFR18	5.60	SFR18	2.51
3	SFR10	5.16	SFR19	2.48
4	SFR15	5.05	SFR10	2.45
5	SFR4	4.81	SFR17	2.35
6	SFR17	4.75	SFR15	2.27
7	SFR7	4.72	SFR9	2.24
8	SFR9	4.68	SFR5	2.18
9	SFR14	4.59	SFR7	2.14
10	SFR5	4.59	SFR12	2.10
11	SFR12	4.48	SFR11	1.99
12	SFR11	4.30	SFR14	1.99
13	SFR13	4.25	SFR13	1.96
14	SFR22	4.11	SFR22	1.92
15	SFR24	3.95	SFR24	1.83
16	SFR25	3.89	SFR25	1.73
17	SFR3	3.63	SFR3	1.73
18	SFR2	3.53	SFR2	1.72
19	SFR23	3.28	SFR6	1.56
20	SFR6	3.25	SFR23	1.54
21	SFR20	2.73	SFR20	1.23
22	SFR1	1.99	SFR1	0.85
23	SFR21	1.05	SFR21	0.55
24	SFR8	0.91	SFR8	0.34
25	SFR16	0.05	SFR16	0.02

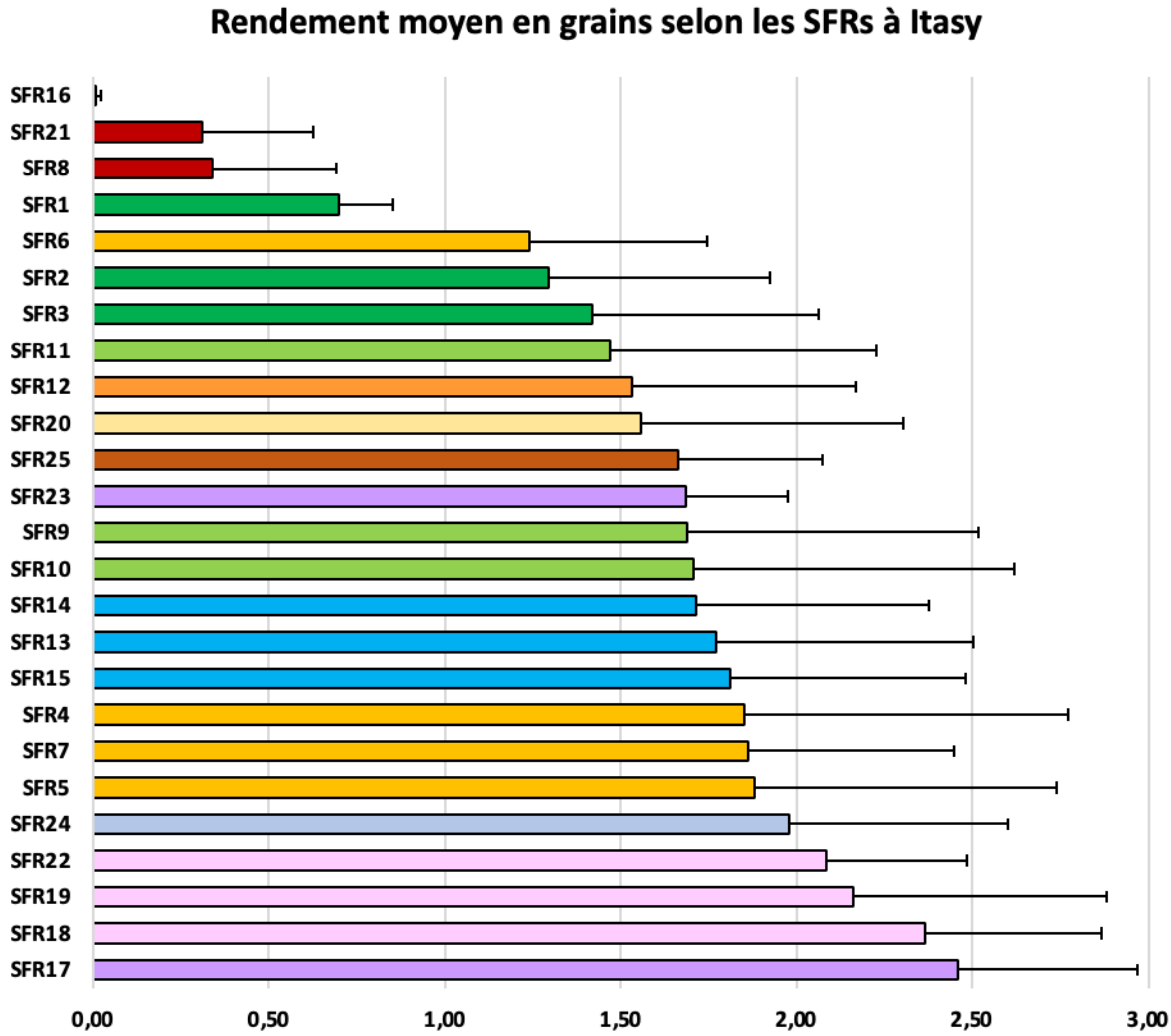
The cells highlighted in yellow are the SFRs whose total biomass is greater than 4.00 t DM/ha

Appendix 22: Ranking of SFRs in relation to biomass production in year 3 (2019-2020) on the Itasy site

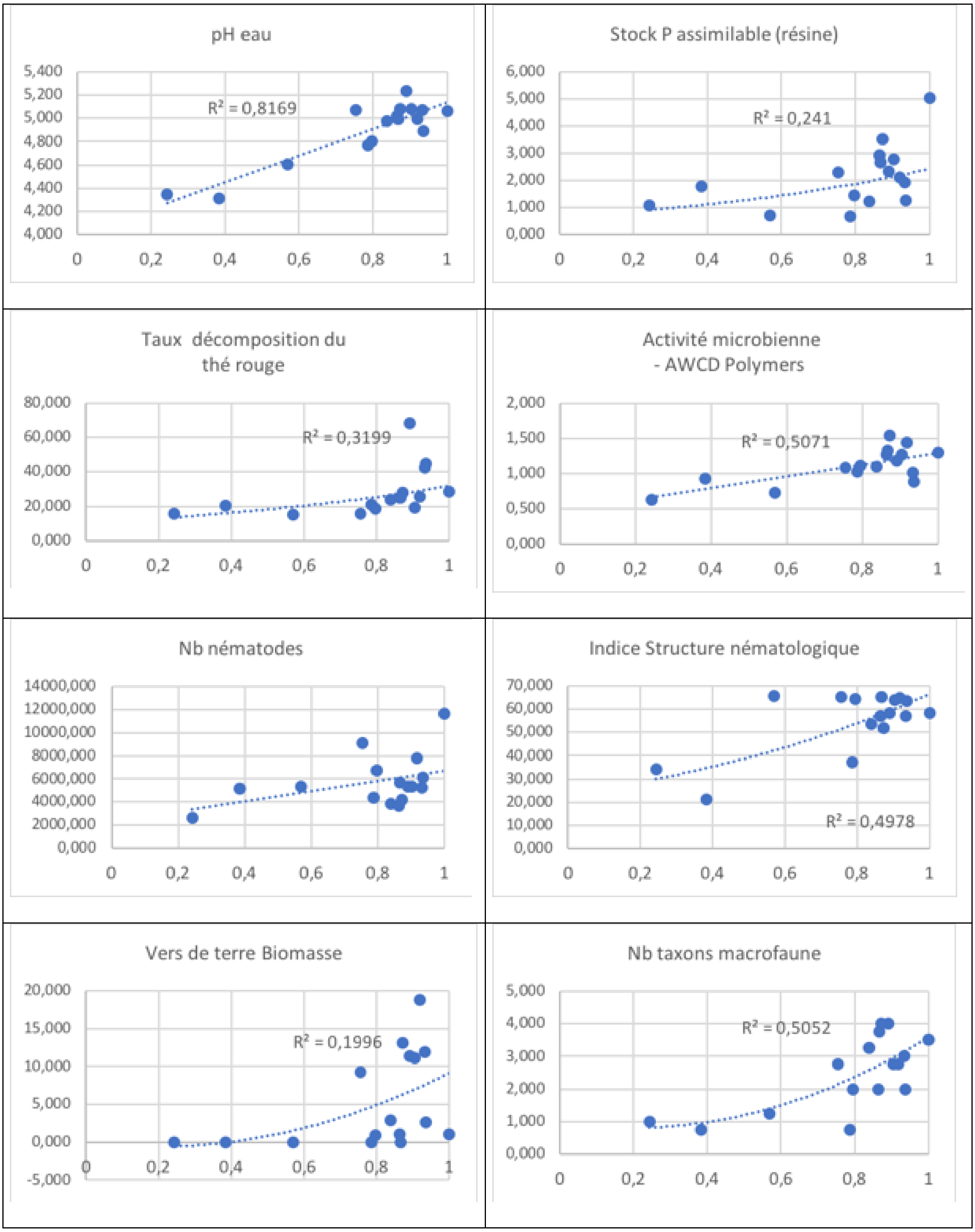
Rang	SFR	Biomasse totale (t MS/ha)	SFR	Grains (t MS/ha)
1	SFR15	7.90	SFR17	2.57
2	SFR23	7.33	SFR5	2.55
3	SFR9	7.13	SFR13	2.46
4	SFR12	6.85	SFR7	2.31
5	SFR22	6.44	SFR22	2.25
6	SFR7	6.34	SFR4	2.24
7	SFR24	6.23	SFR14	2.24
8	SFR17	5.99	SFR9	2.22
9	SFR10	5.98	SFR18	2.22
10	SFR25	5.89	SFR10	2.15
11	SFR18	5.75	SFR24	2.13
12	SFR14	5.64	SFR15	2.09
13	SFR13	5.62	SFR20	1.89
14	SFR11	5.36	SFR19	1.85
15	SFR5	5.35	SFR11	1.84
16	SFR4	5.32	SFR3	1.84
17	SFR20	4.95	SFR23	1.82
18	SFR3	4.82	SFR12	1.66
19	SFR19	4.74	SFR2	1.65
20	SFR2	4.25	SFR25	1.60
21	SFR6	4.16	SFR6	1.45
22	SFR1	2.37	SFR1	0.57
23	SFR21	0.48	SFR21	0.13
24	SFR8	0.24	SFR8	0.12
25	SFR16	0.00	SFR16	0.00

The cells highlighted in yellow are the SFRs whose total biomass is greater than 5.50 t DM/ha

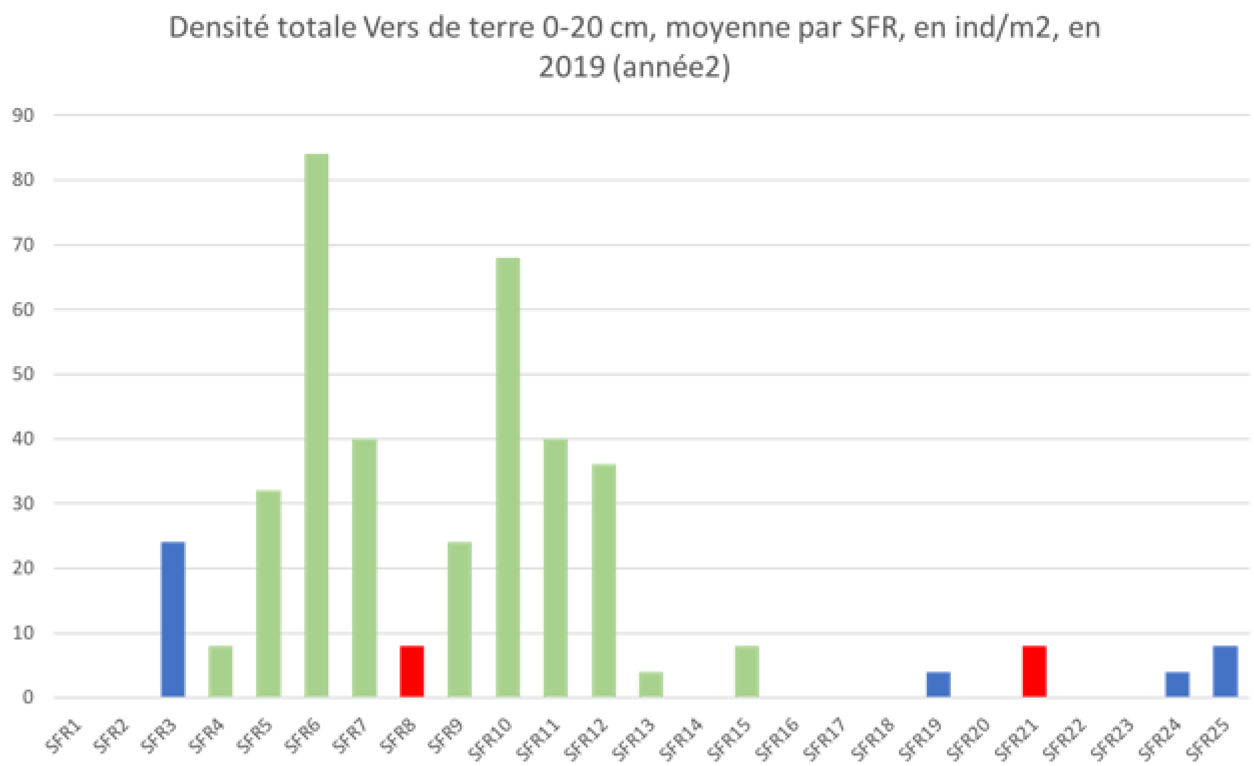
Appendix 23 : Average rice grain yield over the three years of experimentation at Itasy



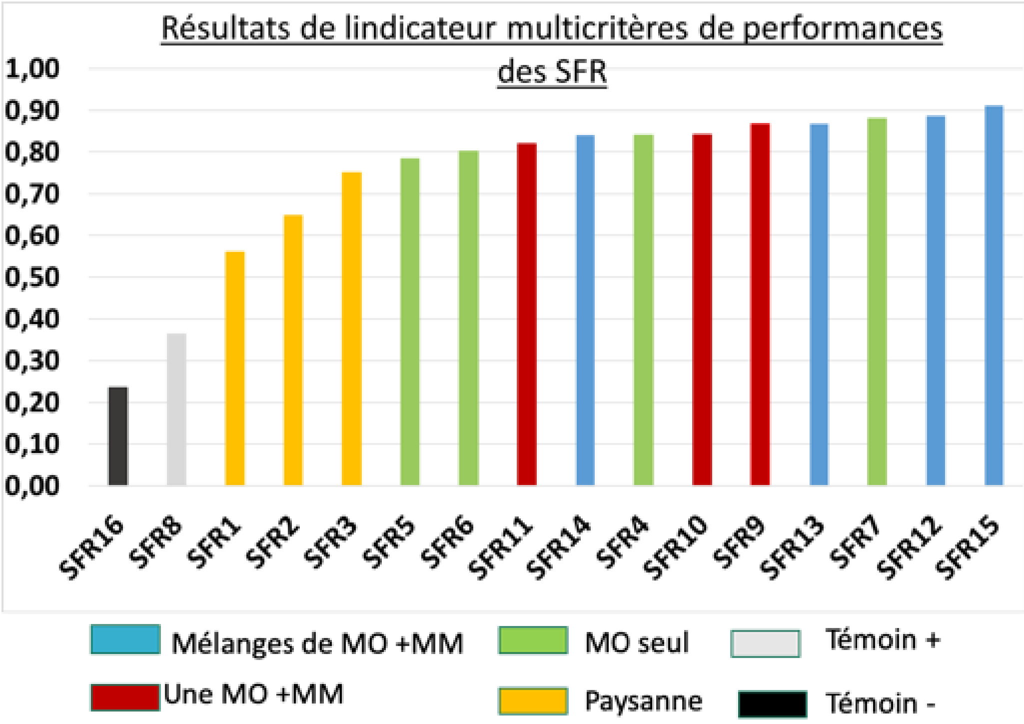
Appendix 24: Positive relationships between the indicator of agronomic performance (linked to rice growth, biomass, yield, grain and straw quality) and different soil biotic and abiotic parameters



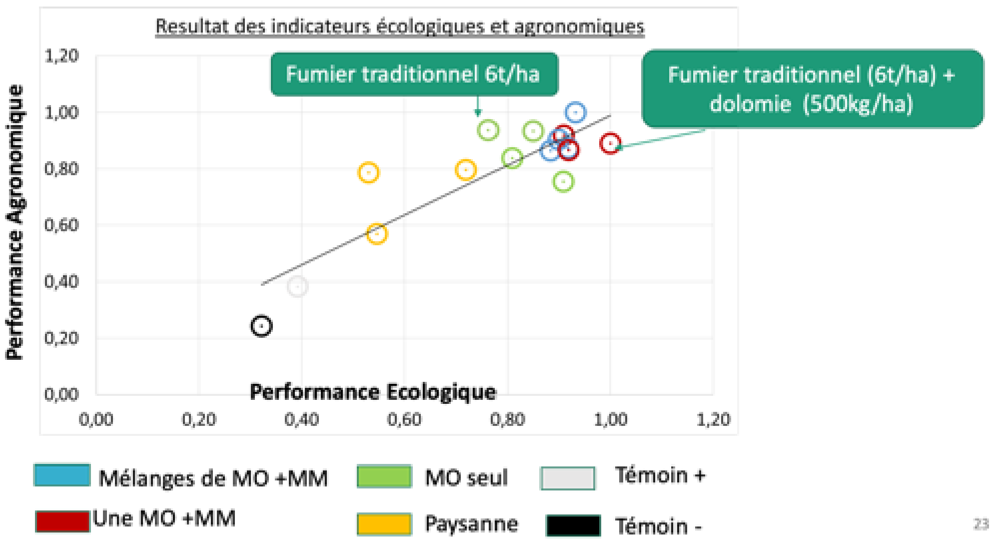
Appendix 25: Mean density of earthworms (0-20 cm) (ind.m^{-2}) in different SFRs at the end of the second cultural year. SFRs where earthworms were inoculated are in green, SFRs where earthworms were not inoculated are in blue and red (controls). This shows SFR where earthworms car find adequate conditions for their development.



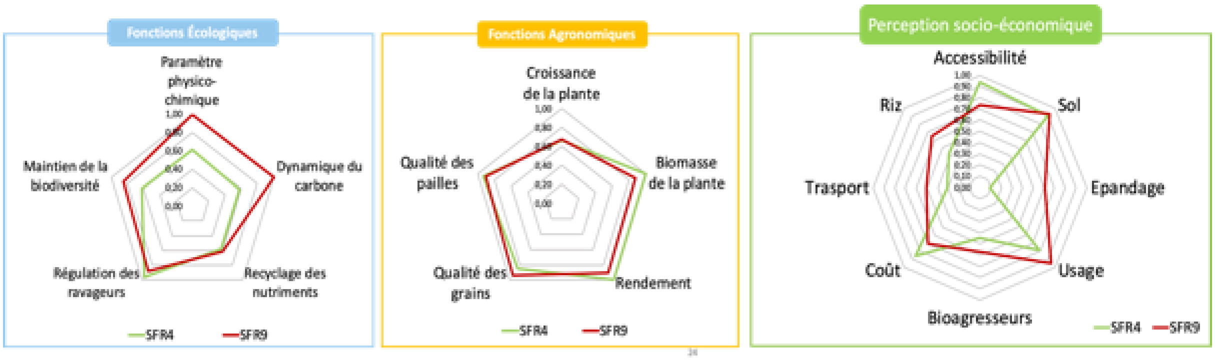
Appendix 26: Multicriteria performance indicator for SFRs in Itasy (after 2 years of experiment)



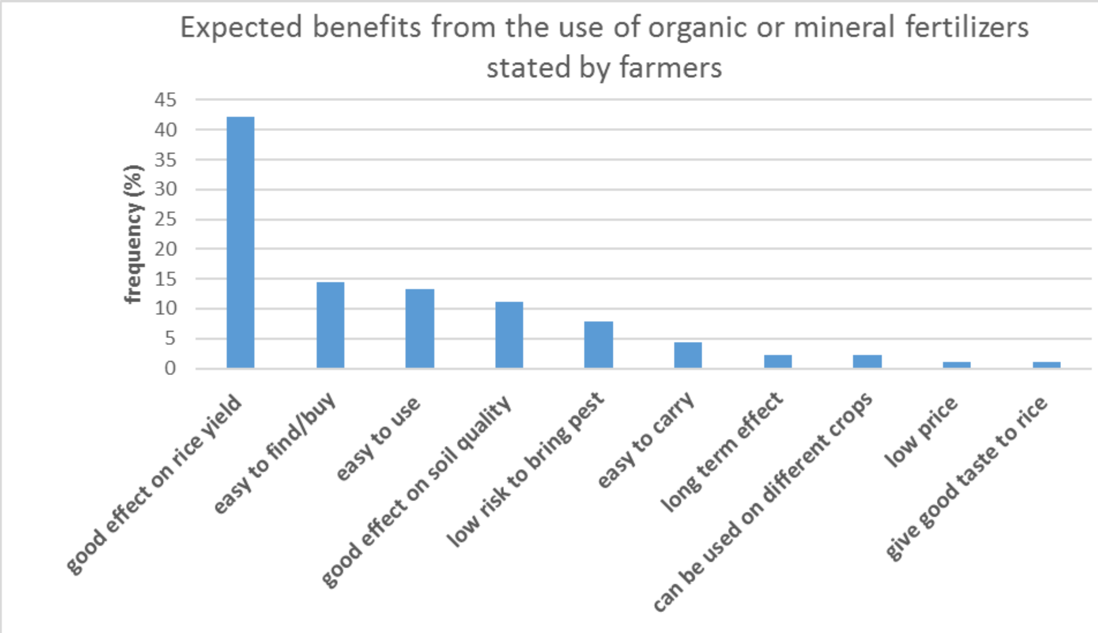
Appendix 27: Relationship between soil ecological performance indicator and agronomic performance indicator



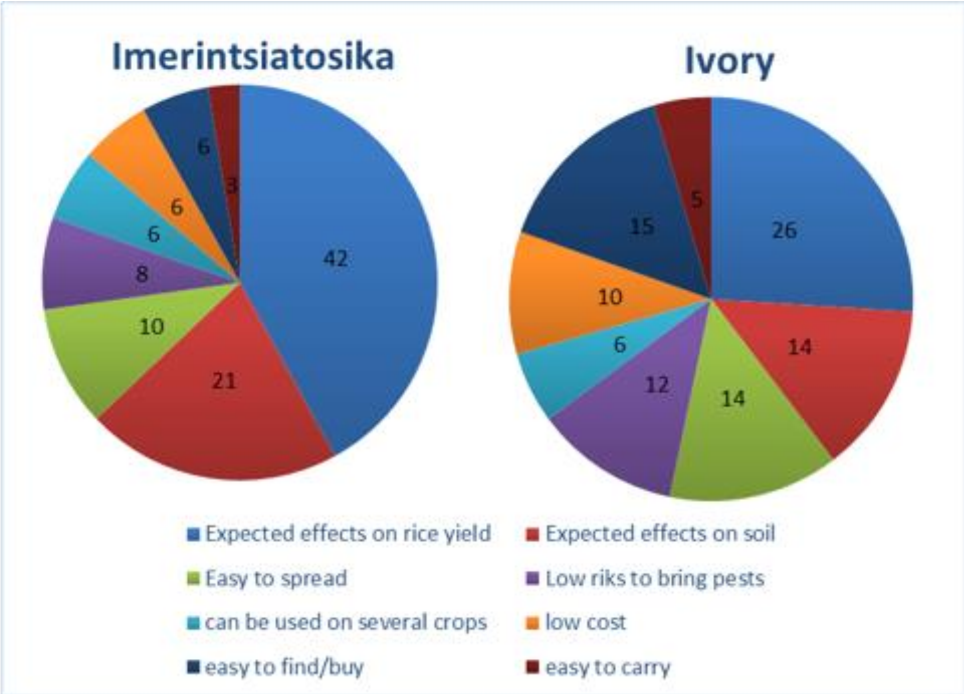
Appendix 28: Comparison of two SF (SFR4 and SFR9) on Ecological and Agronomic indicators divided by functions, and on the socio-economic perception by farmers



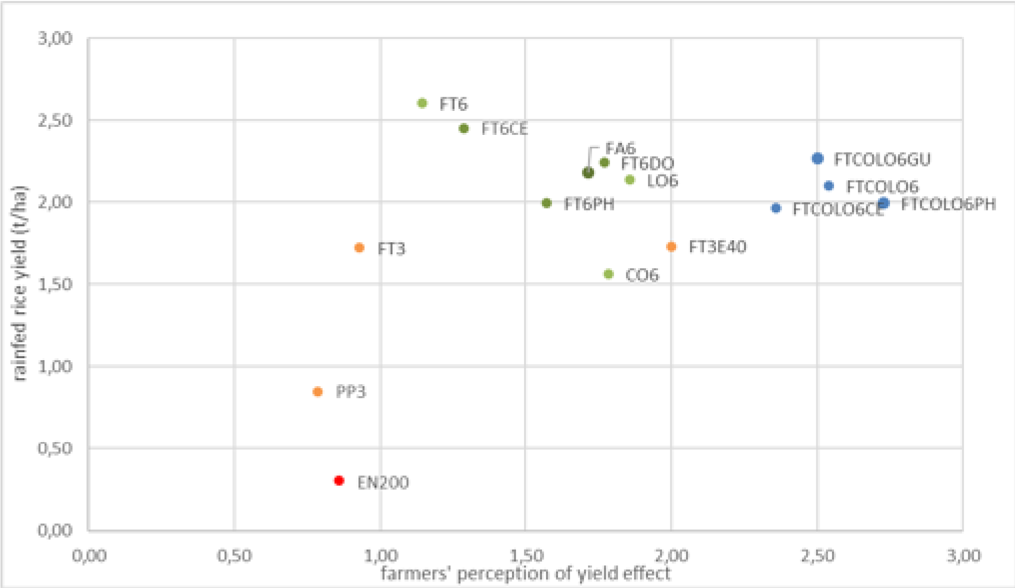
Appendix 29: Frequency of descriptors mentioned by farmers about several organic or mineral fertilizers



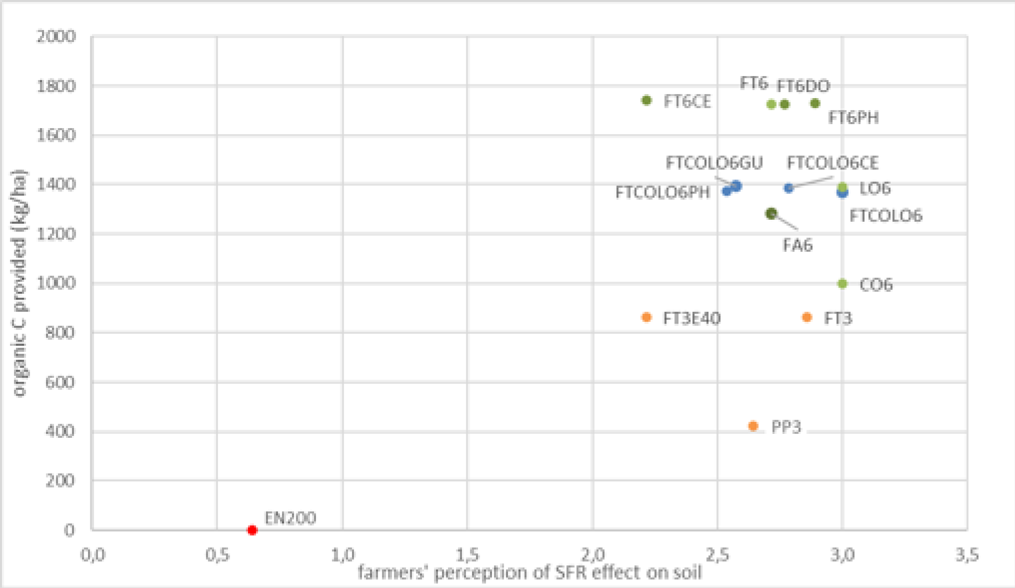
Appendix 30: index about farmers' local knowledge SFR performance



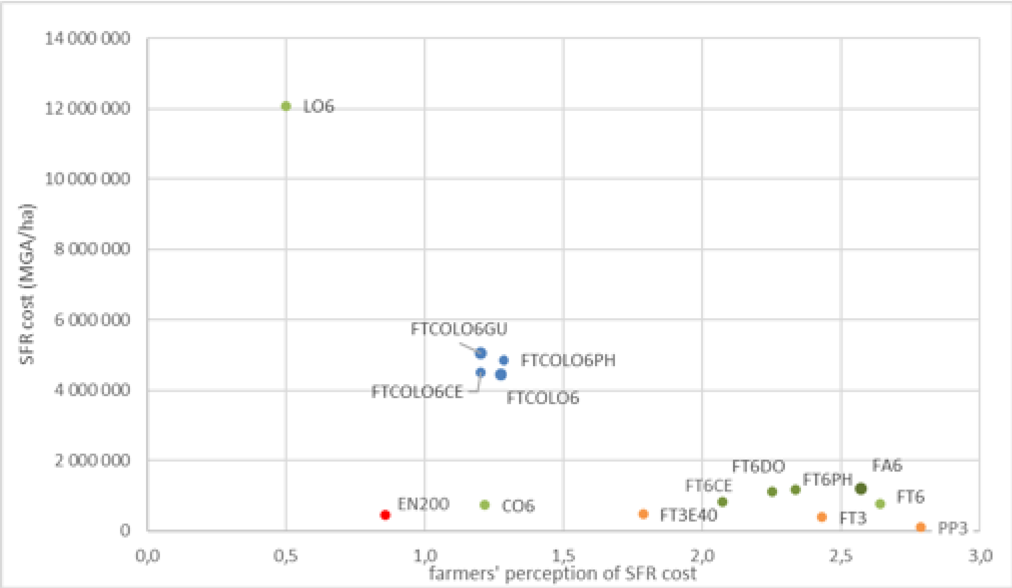
Appendix 31: Crossing farmers' perception with rainfed rice yield in Imerintsiatosika



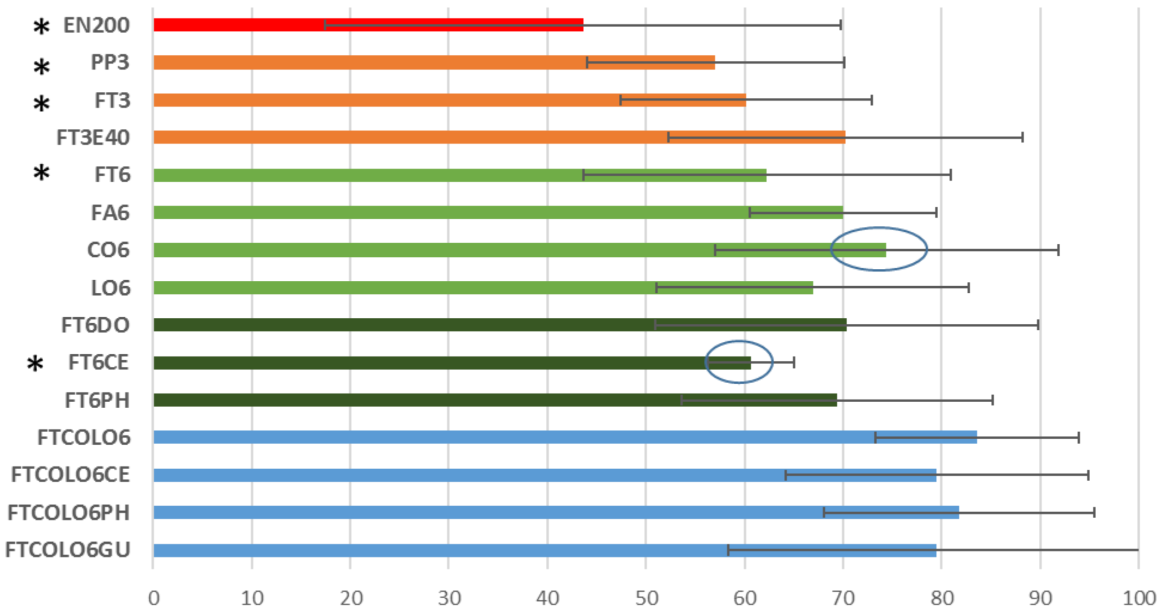
Appendix 32: Crossing farmers' perception with organic C provided in Imerintsiatosika



Appendix 33: Crossing farmers' perception with SFR cost in Imerintsiatosika



Appendix 34: Aggregated index for SFR in Imerintsiatosika site



Appendix 35: Aggregated index for SFR in Ivory site