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Intensifying the soil ecological functions for sustainable agriculture: Acting with stakeholders

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A B S T R A C T

Soils are now recognized as key components in the design of sustainable agricultural practices within the agroecological framework. They are the place of many ecological functions achieved by living organisms interacting with each other and which support the sustainable provision of agrosystem services. In the context of the transformation of agriculture and to improve the sustainability and resilience of family farming, it becomes urgent to promote soil ecological functions, to intensify them by appropriate practices considering the socio-economic constraints, and finally, to be able to monitor them. Here, to improve our consideration of the soil functions for a sustainable agriculture, we first rely on the ecological theories of terrestrial ecosystem functioning to better establish the concept of sustainable functions in agroecosystems. We then propose a methodological framework, called SE-CURE (for "Soil Ecology Cure"), that aims to optimize the ecological functions of the soil for a sustainable supply of ecosystem services. This framework relies on the involvement of stakeholders and is illustrated by a case study in Madagascar where the different steps of the SE-CURE approach have been applied.

1. Introduction

Transition from conventional agriculture to more eco-friendly agroecological practices that better take into account sustainability has been the subject of many studies and reviews (Pretty, 2008; Godfray et al., 2010; Tittonell, 2014). It mainly targets family farming which is the dominant agriculture type worldwide (Lowder et al., 2016). Smallholders in Africa, South-east Asia and South America are faced to many social, economic, edaphic, and climatic constraints, this is particularly true in Africa where per capita food production remains very low (Pretty et al., 2011). Despite a high adaptability and capacity to face current constraints, food production remains low and very vulnerable to environmental or political crisis. Moreover, the need to double food production in a recent future without degrading natural resources reinforces the great and urgent need to improve sustainability and resilience of family farming in these regions (Doré et al., 2011; Pretty et al., 2011; Kuyah et al., 2021). Nevertheless, as highlighted by Duru et al. (2015) and Gaba et al. (2018), there is still a gap of knowledge between agroecological principles and practical applications probably because the relationships between ecological functions - ecosystem services and site-specific agroecological practices are poorly identified. Smallholder farmers from tropical low income countries, generally have low access to external inputs and an ecological intensification considering soil biodiversity and organic resources may be particularly relevant to such farmers. In these environments, particularly on low quality soils (such as Ferralsols or Arenosols), it is urgent and important to improve or restore the capacity of soils to provide ecosystem services (Tittonell, 2016).

In the agroecological transition, the soil occupies a very important place, in accordance with the many ecosystem services (crop nutrition, disease regulation, erosion regulation, climate regulation, etc.) it provides (Keesstra et al., 2016). One of the pioneers of this view was Basil Bensin, promoter of the term "agroecology" at the beginning of the 20th century which he positioned as a science of soil conservation, stressing the importance of the adaptations of plants to specific environmental conditions (Doré and Bellon, 2019). The need to take into account ecological functions to promote the sustainability of agroecosystems was advocated early by M. Altieri (2004). Among the five principles that this author proposes, soil is omnipresent through biodiversity, recycling of nutrients, plant growth, beneficial biological interactions and the promotion of key ecological functions. Numerous scientific publications underline the importance of enhancing soil biodiversity in agricultural systems, acknowledging their ecological complexity and relying on their ecological functions (Altieri, 1999; Barrios, 2007; Brussaard et al., 2007;

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Kibblewhite et al., 2008). This ecological intensification is defined as an alternative approach to conventional intensification, with the objective of maintaining or increasing yields while minimizing negative impacts on the environment (Doré et al., 2011; Bommarco et al., 2013). In the current context of the sixth massive biodiversity loss crisis, characterizing, understanding and optimizing the biological functions of soils within agrosystems is a necessity (Dirzo et al., 2014; Seibold et al., 2019).

In this opinion article, we aim to emphasize the need to optimize functions and interactions in soils for the establishment of multiple agroecosystem services (Liu et al., 2022) and their sustainability. To reach this goal, we aim to propose a methodological framework (SE-CURE for Soil Ecology Cure) to promote the intensification of ecological soil functions based on improved local knowledge on the relationships between biodiversity (organisms) - processes - functions - services (BPFS). The first section recalls the theoretical background which positions the place of the soil in ecosystem ecology and in the conventional management of agrosystems. The methodological sequential approach (SE-CURE) is described in the second section. The third one illustrates this sequential approach with four case-studies that aimed to optimize ecological interactions in soils in order to increase ecological intensification sustainability (sensu Pretty and Bharucha, 2014).

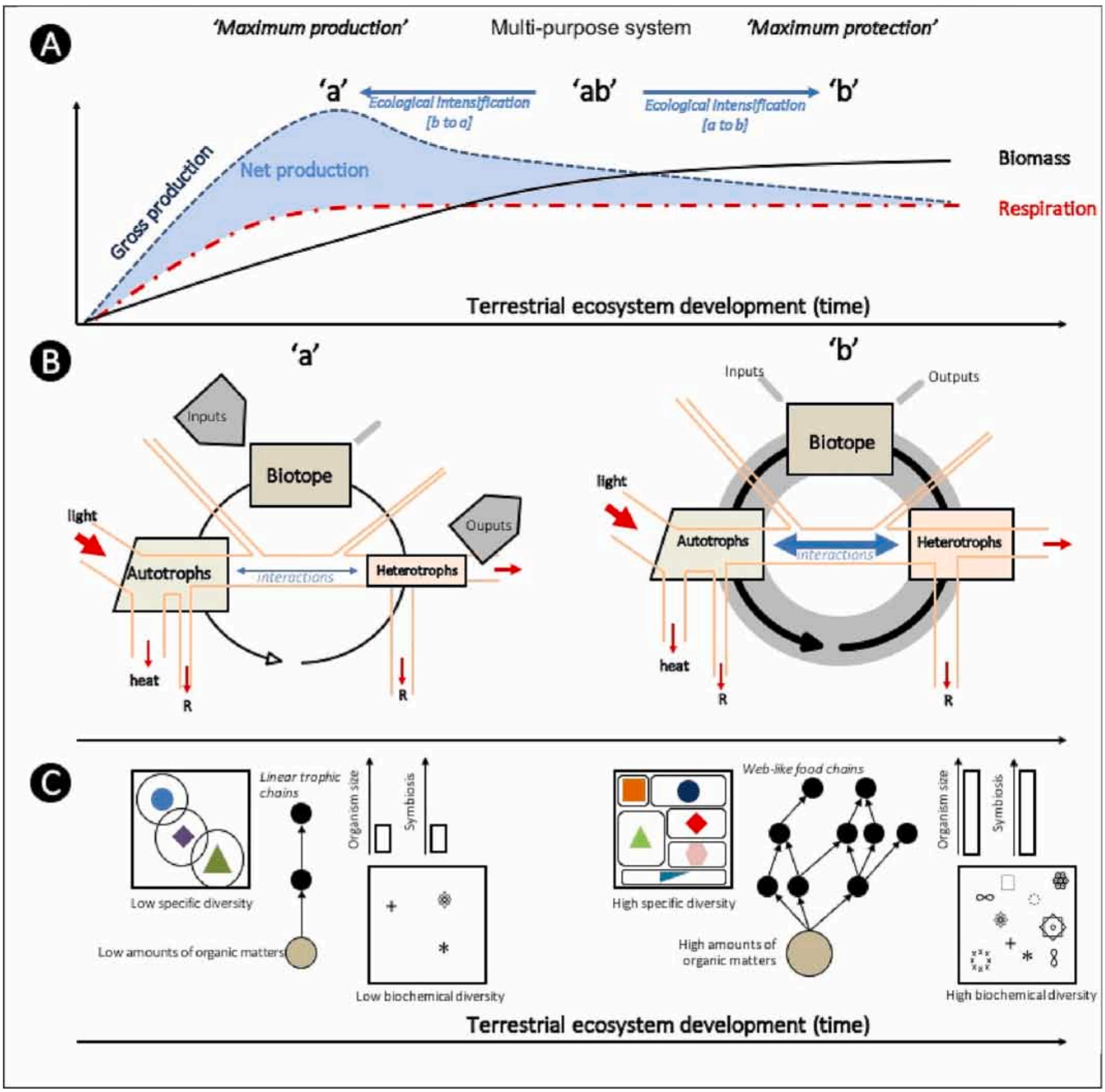

Fig. 1. Positioning intensification of soil processes in the theoretical framework of terrestrial ecosystem development., to combine productivity and sustainability. (A) Biomass production and respiration of terrestrial ecosystems succeeding one another over time. (B) Energy flow and cycle of matter for stages 'a' and 'b'. (C) Biotic properties of stages 'a' and 'b'. Adapted from Odum, 1969

2. Soils in agroecology: a theoretical background

2.1. Agronomy, ecosystem ecology and soil biology

In the middle of the 20th century, as productivist agriculture developed (Wiilson and Rigg, 2003), ecosystem ecology and its associated theories emerged. The theory of the strategy of ecosystem development proposed by Odum (1969), in which soils and its biodiversity occupy a major place, describes the evolution over time of functional properties of terrestrial ecosystems that are not (or only slightly) human-influenced. These properties, or more precisely 'predictions', have subsequently been confirmed in numerous occasions and synthetized by Corman et al. (2019). Briefly, the pioneer stages quickly give way to the most productive stages, consisting of fast-growing plant species, to low productivity mature stages composed of slow-growing species (Fig. 1.A). Although the literature is limited, it is known that the soil mineral fertility, the soil organic matter content and the taxonomic and functional composition of the soil biodiversity also evolve along ecosystem maturation (Fig. 1.B), i.e. the interactions between organisms are accentuated and the closing of the biogeochemical cycles is reinforced (Fig. 1.B). Likewise, the food webs become more complex with the increased presence of heterotrophic organisms, an increase in the average size of the organisms, in the biochemical complexity of organic matter, in the dominance of the energetic fungal pathway, and in the efficiency of carbon (C) capture (Maharning et al., 2009; Morriën et al., 2017; Corman et al., 2019; Shelef et al., 2019) (Fig. 1.C). The set of ecological mechanisms involved in these aboveground and belowground ecological successions (e.g. competition, prey-predator relationships, exploitation of resources, tightening of niches) inexorably leads these productive stages towards biostatic stages (Oldeman, 1990) whose functional properties strongly differ from early stages (Corman et al., 2019). It therefore appears that ecological rules impose an opposition between high productivity and dynamic stability of natural ecosystems. Maintaining a highly productive terrestrial ecosystem means opposing succession ecological mechanisms. To fight against this law of nature (Colyvan and Ginzburg, 2003), there is only one solution: inject energy. Since a majority of the ecological mechanisms involved in successions operate within soils, the injection of energy into the soils is central in order to maintain high productivity, e.g. soil tillage, pesticide addition to control pathogens and weeds, mineral or organic fertilization to improve plant yields, etc. The question of the sustainability of this soil management arises.

2.2. The importance of ecological intensification of soil functions for the sustainability of the service provision

The energy invested in agrosystems temporarily allows controlling all of the ecological mechanisms which would inexorably lead to a less productive state of functioning. Maintaining a continuous energy supply is not enough, however, to achieve sustainable production targets. A continuous, or punctually massive supply of energy within the agrosystem can induce drastic changes in the functional properties of the ecosystem, which can lead to major 'dysfunctions' (abnormal or impaired functioning) in the long term (Reganold et al., 1987; Pimentel, 2006). This refers to the ecological resilience of ecosystems (Holling, 1996; Griffiths and Philippot, 2013). For example, excessive use of chemical fertilizers promotes an increased mineralization of soil organic matter, leading, among other phenomena, to a reduction in the relative abundance of certain beneficial mutualist strains for the benefit of pathogenic strains (Johnson, 1993; Gryndler et al., 2006). These practices, although initially implemented to increase and maintain the productivity of agrosystems, tend to impair the sustainability of the provision of ecosystem services such as food production.

The soil biological properties found in mature ecosystems permit a 'near-sustainable' functioning in the sense that they do not oppose the succession rules. Observing, analyzing and describing with accuracy the soil functioning within these ecosystems is central to understand the links between the biological properties of soils and the sustainability of the functioning of ecosystems. It is important to emphasize that the succession dynamics do not lead to an optimization of soil functions for the production of a desired ecosystem service (Odum, 1969). Thus, the ecological intensification (or ecological engineering) of soil functions, here defined as a set of techniques aimed at maximizing the provision of ecosystem services by an appropriate management of soil biodiversity, while minimizing the impact of ecological mechanisms of succession dynamics, gives agrosystems a better ecological resilience and a greater sustainability (Yachi and Loreau, 1999). For this, the soil ecologists the agronomists and the farmers, must identify (i) the ecological functions that can be targeted by particular agronomic levers to implement them within system management and (ii) the relevant tools able to accurately monitor the restoration of soil functions. The farmer point of view is essential to ensure the feasibility, acceptability and viability of the practices and the monitoring tools.

3. 'SE-CURE' (Soil Ecology CURE): a sequential framework for the ecological intensification of soil functions in family tropical farms

Soil organisms, free-living and symbiotic forms, play major roles in the functioning of agrosystems and the sustainability of the provision of ecosystem services (Barrios, 2007; Brussaard et al., 2007; Clermont-Dauphin et al., 2014). The functions played by these organisms result from multiple processes and interactions between them and with their habitat which structures the ecological networks in soils (El Mujtar et al., 2019). In the actual context of global biodiversity extinction crisis, it appears urgent (i) to improve our understanding of the determinism of aggregated functions, especially the biodiversity-process-function relationships, (ii) to identify the agronomic levers, in perfect harmony with local constraints to maximize adoption, which allows to drive these soil functions and interactions in a frame of soil ecological intensification and in the maintenance of the provision of ecosystem services, and (iii) to evaluate and monitor this soil functions.

Two approaches are currently proposed to promote biological soil functions. The first, most common, consists of setting up farming systems perceived as sustainable or agroecological and making, after one or several cropping seasons, a diagnosis of soil biodiversity and/or biological activity to verify that it responds positively to alternative practices (Altieri, 1999; Henneron et al., 2015; Tamburini et al., 2020). In this approach, soil biodiversity and its functions are not the targets of system design but an unmanaged response to these agricultural practices; they are therefore considered as response indicators of soil quality, with the preconceived, still debated, idea that these indicators are directly related to a sustainable intensification of soil functions. This approach has resulted in a proliferation of tools and indicators seeking to rapidly and globally describe soil health. A healthy soil is defined as a stable system with high levels of biological diversity and activity, internal nutrient cycling, and resilience to disturbance (Rapport, 1995; Verhulst et al., 2010). It is generally accepted that the more abundant or diverse the soil organisms, the more likely the soil functions will be improved and the more sustainable the system will be. But this hypothesis is not always verified because of our lack of knowledge on biodiversity-process-function relationships in soils. Many studies showed that an increase in abundance or richness of soil organisms is not always associated to improved soil functions (Laakso et al., 2000; Cragg and Bardgett, 2001; Postma-Blaauw et al., 2006; Nielsen et al., 2011; Trap et al., 2021b). For instance, in the West Indies, an increase in earthworm density had no effect neither on soil structure nor carbon content in Vertisols (Blanchart et al., 2004). Similar patterns have been found for soil chemical properties such as organic matter content and plant productivity (Oldfield et al., 2020). These facts question the functional value of chosen soil (biological) indicators.

Another less common approach is to intensively target genuine soil ecological functions which cause agrosystem dysfunction, i.e., a service (or several) is (are) not provided and/or that the agricultural practices are not sustainable. For instance, agrosystem performance can be constrained by impaired soil functions such as erosion, nutrient deficiencies, lack of organic matter, soil-borne diseases, reduced soil infiltration, which could be improved or restored by managing relevant soil biodiversity. To be able to propose management alternatives, it is therefore necessary to study and understand, at a local level, the BPFS relations. We include these needs in a sequential framework called SE-CURE (for Soil Ecology Cure) to ensure the success of the intensification of the soil functions (Fig. 2).

Step 1: Co-diagnosis of local dysfunctions (State).

Associated questions: what are the local constraints limiting agrosystem services or impeding agrosystem sustainability? Is the constraint a soil problem for which an ecological intensification of soil function can be a solution?

The sustainability problems encountered in agriculture and the alternative practices supposed to promote soil functions are rarely contextualized. Interactions with farmers and/or land users associated with a thorough assessment of limits, vulnerabilities and constraints of the agrosystem may help to reveal the dysfunctions. We thus believe that, using a participatory approach, and through surveys and workshops, a first exhaustive assessment of the local vulnerabilities and agrosystem dysfunctions in terms of soil erosion, low fertility, low carbon content, high pathogen pressure, etc., is necessary. This local assessment must also list the internal constraints of smallholder farms (e.g., working force, time schedule, poverty, lack of animals, etc.) and external constraints (e.g. access to markets, poor infrastructure, inadequate education and training, access to technology and information, unfavorable government policies or regulations, etc). After this first participatory assessment of local constraints and the main factors that limit sustainability of agrosystems, there is a need for soil scientists and farmers to identify (or validate) which ecological function(s) is(are) disturbed. For this, the soil properties and functions are assessed by measuring several biological, physical and chemical parameters, such as (1) biological: diversity and abundance of soil organisms including earthworms, total macrofauna, nematodes, microbial communities, pests; (2) physical: gravimetric water content, texture, compaction, water infiltration or aggregation; (3) chemical: contents in carbon and nutrients, nutrient availability, pH, ion-exchange capacity, organic matter dynamic (e.g., litter bag, bait lamina). These non-exhaustive, standardized and basic analyses provide a synoptic view of the soil quality that is complemented by the local knowledge of the farmers.

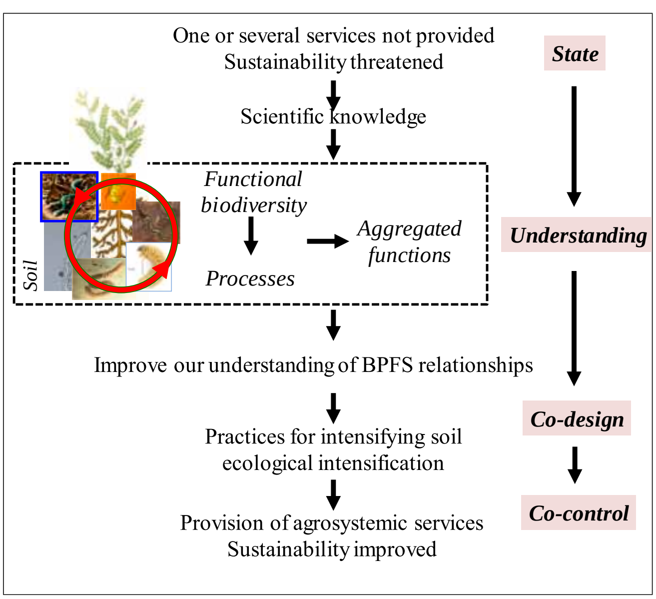

Fig. 2. Diagram illustrating the SE-CURE (Soil Ecology Cure) methodological approach allowing to optimize the soil ecological functions for the sustainable provision of ecosystem services. Legend: Relations BPFS = links between Biodiversity-Processes-Functions-Services.

Step 2: Scientific knowledge in BPFS relationships at the local scale (Understanding).

Associated question: which soil ecological processes could be enhanced by agricultural practices to improve or restore targeted soil aggregated functions?

The main soil aggregated functions resumed by Kibblewhite et al. (2008) are nutrient recycling, carbon transformations, soil structure maintenance, and pathogen regulation. The determinism in these soil aggregated functions and the causal relationships between practices-biodiversity-processes-functions are still poorly known (Kuyper and Giller, 2011; Thakur et al., 2020). This is probably because each of these aggregated functions results from multiple ecological processes involving different soil organisms in complex interactions. For instance, soil phosphorus (P) availability for crops results from a set of biological and physico-chemical processes, e.g. mineralization of organic P, solubilization of orthophosphate ions, diffusion, modification of sorption-desorption kinetics, soil exploration, etc. (Fardeau et al., 1991; Oehl et al., 2001; Khan et al., 2009; Achat et al., 2013; Plassard et al., 2017). There are standardized tools that measure the concentration of the orthophosphate ions in the soil solution using saline extraction (Olsen, 1954), or using ion exchange resins. These tools, although commonly used, do not allow to identify the process(es) involved but to access a quantification of a P pool. On the other hand, there are other tools that allow access to the different fluxes of the P cycle and to identify precisely the processes involved or defective. A second reason lies on the determinism of the BPFS relationships which is likely to take various features at local scales (Delgado-Baquerizo et al., 2020). We therefore believe that the tools to understand BPFS links must be deployed locally and directly target the soil processes to provide an accurate and integrative understanding of the causal relationships between local soil biodiversity and soil processes.

Based on the first evaluation of the agrosystem context and the local soil properties, it is necessary to deeply study the interactions between agricultural practices, soil habitat, soil biodiversity, processes and functions in order to understand (i) which organisms or biological metrics (functional groups, functional traits, taxonomic richness, etc.) could be monitored in relation to the dysfunction, and (ii) which driver(s) should be implemented to improve the desired biodiversity and ecological processes? Complementary approaches (field trials, laboratory or greenhouse experiments, modelling, etc.), simple standard or cutting-edge techniques can be performed. The contrasting approaches in both controlled environment and field trials may provide a detailed mechanistic understanding of the relationships between practices, soil biodiversity, processes, functions, and services.

Step 3: Testing innovative agricultural practices focusing on soil biological functions (Co-designing).

Associated question: what local socially and economically integrated agricultural practices, co-designed with farmers, can be implemented to improve or restore the desired soil function(s)?

In an interdisciplinary approach involving sociologists, agronomists, ecologists and farmers, agricultural practices that allow for both an ecological intensification of soil functions and an improvement of agronomic performance are proposed through workshops in a participatory research context. More specifically, this step includes co-learning workshops on scientific and traditional knowledge of soil functioning, as well as co-design workshops for the restoration of soil biological functions, taking into account socio-economic constraints. The trials resulting from these workshops target different agronomic levers for restoring ecological functions of soils, such as organic-mineral fertilization, plant diversity, genetic improvement, or bio-fertilization, anti-erosive implements, mulching. Ecological soil intensification practices are not exclusive of other agroecological practices and require advanced engineering combining several disciplines. Any innovative agricultural practice that directly or indirectly manages targeted soil biodiversity should be considered. These innovative practices are tested in multi-local trials or in experimental fields to evaluate the technical, social and economic feasibility. All stakeholders are involved in the design and the evaluation of the practices. The evaluation of practices is carried out by field visits and ratings based on agronomic and ecological criteria previously discussed in a group workshop.

Step 4. Co-evaluating the effects of innovative practices on soil functions (Co-control).

Associated question: what tools can be used to evaluate and monitor soil functions?

Finally, the last step of SE-CURE consists of co-evaluating the agronomic performance of innovative systems and linking it to the ecological intensification of soil functions. Agronomic and ecological performances are evaluated by farmers based on their perception, as well as by scientists. The tools used to characterize the intensification of ecological soil functions must be perfectly adapted to the local context and the targeted dysfunction identified in the first step. As quoted earlier (Step 2), beyond properties, we need to measure both the aggregated functions and specific soil processes requiring cutting-edge techniques. The choice of tools used to monitor soil functions depends on: (i) the biodiversity and functions to be monitored, (ii) the cost of the tools and their availability and (iii) the local technical feasibility. Finally, the user

Fig. 3. Illustration of the SE-CURE approach to intensify soil function in the upland rainfed rice agrosystems in the Itasy region from Madagascar. (A) Participatory workshop with farmers to identify agronomical, ecological and economic constraints (step 1). (B) Laboratory experiments to characterize soil properties and functions (step 2). (C) Working groups with farmers to discussed the scientific knowledge from the previous step (step 3). (D) Large co-designed field experiment testing innovatice practices. (E) Field experiment set-up. (F) Evaluation of the innovatice practices by the farmers and the scientists. (D) Working group discussing the main results following practice evaluation.

must base his choice on a compromise between the efficiency (ability to accomplish with le least amount of time, money and effort) and the effectiveness (degree to which something is successful in producing desired results) of the tools. But importantly, these indicators have to be directly related to the causal relationships between practices-biodiversity-processes and aggregated functions, to provide a sustainable intensification of soil functions. They result from the three previous steps of SE-CURE and should not be generic or pre-defined methods. The co-selected innovative practices must be communicated to as many people as possible. This dissemination can be done in various ways, such as producing booklets and brochures in the local language, setting up workshops to share results with users, producing summary documents for policymakers, disseminating messages through media and social networks, and providing academic training.

4. Illustration

Here, we reported a case study in Madagascar where the different steps of the SE-CURE approach have been applied.

Step 1- Co-diagnosis of local dysfunctions (State).

The yield of rainfed upland rice in the Ferralsols of the Highlands of Madagascar is low, less than 1 t per hectare, and highly variable according to environmental conditions. This leads to lean periods that can be long, causing food insecurity. To understand the main constraints, we first conducted participatory workshops, surveys and visits to plots with producers (Fig. 3.A). We also sampled the soil to analyze its physico-chemical properties and its microbial and faunal biodiversity. Our aim was to identify what are the pedo-ecological, agronomical and economic factors the Itasy region corresponding to the area of study. This work led to the following conclusions: Ferralsols exhibit low pH, low nutrient and organic matter contents, aluminum toxicity and low biological activity. One of the empirical observations of the farmers, in agreement with the soil analyses, is the presence of manure coarse residues at the end of the growing season suggesting very low organic matter decomposition. The survey showed that mineral fertilizers are too expensive for smallholders that use organic amendments, especially cow manure, at low rate. But, organic amendments by farmers are limited and dispatched between different uses, especially market gardening crops. Consequently, rainfed rice crops are weakly amended; and when amended, farmers use all available resources regardless of their biochemical quality. Rice growth and nutrition are strongly conditioned by the mineralization of organic matter in the soil and the availability of nutrients. The low biological activity is probably responsible for the low organic matter decomposition.

Step 2- Scientific knowledge in BPFS relationships at the local scale (Understanding).

We then conducted field trials and laboratory experiments to better understand the soil biological functioning and nutrient limitations (Fig. 3.B). A first nutrient-omission trial showed that these soils are deficient in many nutrients (multiple co-limitation), but especially by phosphorus (P), nitrogen (N), calcium (Ca) and magnesium (Mg) (Raminoarison et al., 2019). In parallel, a second series of field and laboratory experiments revealed that these soil with low organic matter contents are exposed to priming effect (Bernard et al., 2022; Kuzyakov, 2002). Priming effect results from different processes involving microbial actors, their own physico-chemical determinants and targeting different compartments of organic matter (Fontaine et al., 2003). This lack of clear understanding challenges the management of organic matter in the sense that, depending on the processes involved, the PE could stimulate either humification or favor the release of stabilized organic matters characterized by longer residence times (Razanamalala et al., 2018). Using a combinatory approach in a greenhouse experiment and at the field scale, we showed that combining different biological and chemical fertilizing materials is required to fill all the nutrient deficiencies of these soils without inducing large PE. These experiments allowed us to target the quality and quantity of fertilizer materials available in Madagascar as a key agronomic lever.

Concerning the biological activity, we then showed that endogeic earthworms have the ability to increase the plant-availability of nutrients, in particular P, from the soil organic matter (Ratsiatosika, 2018; Trap et al., 2021a). The interaction between plants and earthworms should therefore be optimized. However, the rice cultivars that have allowed the development of rainfed cultivation in Madagascar are the result of breeding programs mainly focused on the tolerance of the plant to cold or to certain pathogens, under highly fertilized conditions. The selection of certain agronomic traits may modify the value of the functional and interaction traits of the cultivated plant involved in the plant-organism relationships of soils (Litrico and Violle, 2015). It is therefore likely that the selection of cultivars effective for the use of nutrients in high concentration in the soil solution will alter the beneficial nutritional interaction between rice and soil organisms. A greenhouse mesocosm experiment tested this hypothesis by examining the ability of six rice cultivars to interact with the endogeic, peregrine earthworm *Pontoscolex corethrurus* (Ratsiatosika et al., 2021). After 2 months of growth, all cultivars responded positively in terms of growth and nutrition, to the presence of earthworms, compared to situations without earthworms. However, the magnitude of the response (the effect size) was highly variable. The presence of earthworms increased rice biomass from 40% to 130% depending on the cultivar. The variability in the positive response of rice to the soil engineer according to the cultivar was also observed for nitrogen (N) (from 116% to 355%) or P (from 48% to 147%) nutrition. Our results showed that earthworms are very important actors in providing available P to the crops and plant genetic improvement, by promoting efficient genotypes with regard to a particular agronomic criterion, can strongly impact the plant to interact with soil organisms and optimize the processes involved in the supply of nutrients.

Step 3- *Testing innovative agricultural practices focusing on soil biological functions (Co-designing).*

These results were transferred and discussed with farmers in working groups (Fig. 3.C). We identified key levers: the fertilization based on combined materials, the presence of earthworms and the plant cultivars. The most promising combinations of materials were identified according to their fertilizing interest but also to their availability or their price in order to facilitate the adoption of practice. The fertilizing materials have been classified in functional groups allowing the farmer to choose the materials according to different criteria. Following Razanamalala et al. (2017), it has been proposed that a regular supply (3–4 times per cropping season unlike a traditional single supply at the start of the season) of fertilizer materials could maintain the activity of soil organisms and may limit the stimulation of the release of stabilized C by the microbial community (Razanamalala et al., 2018). With farmers, we then co-designed a field experiment testing innovative practices based on combined organic material and earthworm inoculation with earthworm-responding rice varieties (Fig. 3.D & E). This trial was monitored during four years.

Step 4- *Co-evaluating the effects of innovative practices on soil functions (Co-control).*

Finally, we co-evaluated the agronomic performance of innovative systems and linking it to the ecological intensification of soil functions (Fig. 3.F & G). Agronomic and ecological performances are evaluated by farmers based on their perception, as well as by scientists. We identified promising rice varieties that respond to earthworm inoculation and organo-mineral fertilization adapted to altitude and not sensitive to the blast disease (Blanchart et al., 2020). The use of ash from rice husks, pig slurry and manure seems to be a complex amendment making it possible to fill a large number of nutrient deficiencies. The dose must nevertheless be sufficiently large and the questions of production of fertilizers persist. We also identified the need to carefully monitor earthworm populations in order to quickly detect declines. In the tropics, the TSBF methodology (Anderson and Ingram, 1993), i.e. manual sorting of earthworms in soil blocks of defined soil volumes, has proven to be efficient for assessing mean earthworm abundance and biomass. An objective is to reach, with time and adequate practices, biomass higher than 30 $g.m^{-2}$ live weight to positively improve/restore soil and plant functions (Spain et al., 1992). Quantifying surface casts is not representative of endogeic earthworm activity. Regarding plant nutrition, it seems important to monitor, over years, the quantity of nutrients (especially N and P) absorbed by plants.

5. Conclusions

In this paper, we reiterate the need to optimize soil ecological functions and biological potential for the development of innovative agricultural practices and the provision of multiple agrosystem services. The sustainability of agrosystems and the multiple production of their services require a better understanding of the links between soil biodiversity-processes-functions-services and between practices and soil ecological functions, and a better management of soil biodiversity. For this, several goals should be pursued: (i) develop long-term field trials in order to understand the above-mentioned links, to manipulate practices, with farmers, so as to follow the evolution over time of biological populations, soil and plant properties; (ii) develop models aiming to predict the evolution of soil ecological functions following practice changes or an inoculation of key organisms, e.g. earthworms, (Blanchart et al., 2009); (iii) there is still a need to develop tools adapted to the local context, directly related to the causal links between soil biodiversity-processes-functions and, if possible, services. Some tools can be very simple but are generally difficult to interpret while other that need time, money and scientific expertise are difficult to implement; (iv) there is a great lack of knowledge on the link between soil biodiversity-soil functions and nutritional quality of crops; (v) there is also a lot of knowledge to be gathered to understand how climate change will affect the above-mentioned links; (vi) finally, we consider that teaching soil ecology should be reinforced, especially in schools of agronomy, but also in the continuing education of farmers. The integration of ecosystem ecological rules in 'nature-based solutions' appears as a means of improving the sustainability of these systems. To succeed in the intensification of ecological soil processes for sustainable agriculture and to provide ecological insurance and resilience to disturbance, we proposed a conceivable methodological framework that can be deployed and used in many terrestrial agrosystems around the world.

Compliance with ethical standards

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Conflict of interest: The authors declare that they have no conflict of interest.

Declaration of Competing Interest

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

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