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Abstract summary

With the development of agroecology, soil plays a particularly important role in the design of sustainable agricultural practices. The soils are the place of many processes operated by living organisms interacting with one another. Soil biodiversity performs various processes which determine the main aggregated functions and finally agrosystem services and sustainability. The understanding of these relationships is particularly important in a global context where biodiversity, including the soil one, is highly threatened. It becomes urgent to promote these ecological processes, to intensify them by appropriate practices considering the socio-economic constraints, and finally, to be able to measure them. Revisiting the ecological theories of the terrestrial ecosystem functioning is a need to improve our consideration of the soil in the agroecological transition. This theoretical approach is illustrated by four studies conducted in the tropics demonstrating the possibility to intensify the soil ecological processes and to solve agronomic dysfunctions. Finally, we highlight the need to define soil indicators based on ecological processes for an appropriate measurement of this intensification and we propose a methodological framework to optimize soil ecological functions for a sustainable supply of agrosystem services.

Keywords: Ecological intensification, agrosystem services, co-construction, indicators of functioning, soil biodiversity, sustainability

Introduction, scope and main objectives

The transition from intensive agriculture to more environmentally friendly agroecological practices that better reflect the expectations of sustainability and development has been widely documented. In these agroecological dynamics, soil occupies a very special place, in agreement with the numerous ecosystem services (plant production, pathogen regulation, carbon storage, climate regulation, etc.) it provides (Keesstra *et al.,* 2016). Many studies stress the need to promote soil biodiversity in cultivated systems, to assume their ecological complexity and to rely on ecological processes (Brussaard *et al.,* 2007). This ecological intensification is defined as an alternative approach to conventional one, with the objective to increase agrosystem services while minimizing negative impacts on the environment (Bommarco, Kleijn and Potts, 2013). In the current context of the sixth massive biodiversity extinction crisis, characterizing, understanding and optimizing soil biological functions within agrosystems is a urgent necessity (Dirzo *et al.,* 2014).

The ecologist E.P. Odum published in 1969 the strategy of terrestrial ecosystem development. In this paper, he described the development of ecosystem properties along ecological successions and highlighted the conflict between the 'maximum protection' and the 'maximum production'. Briefly, the pioneer stages quickly give way to the most productive, early, and transitory stages, consisting of fast-growing plant species, then to low-productivity mature stages composed of slow-growing species. During these successions, soil mineral fertility, organic matter content, the taxonomic and functional composition of edaphic biodiversity are also changing, the interactions between the organisms are accentuated and the closure of the biogeochemical cycles is reinforced. Similarly, the food web becomes more complex with the increased presence of heterotrophic organisms, the average size of organisms increases, the biochemical complexity of organic matter increases, the energetic fungal path becomes dominant and the carbon uptake efficiency increases (Morriën *et al.,* 2017). Ecological rules thus impose an opposition between a high transitory productivity and the dynamic stability of natural ecosystems. Maintaining highly productive terrestrial ecosystems means fighting against successional ecological mechanisms and requires a lot of energy. During the last decades, this energy was provided by tillage, mineral and organic fertilization, pesticides and herbicides. This is ecologically contrary to sustainability, and this justified the development of agroecology and the need for ecological intensification of soil processes (EISP). EISP aims to maximize agrosystem services provided by soil biodiversity while conferring better ecological resilience and sustainability (Yachi and Loreau, 1999).

Here we propose a methodology of soil ecological intensification based on ecological theories with the aim to deliver agrosystem services. Different results from past and ongoing projects in the tropics will be given to validate this approach.

Methodology

We propose a procedure for intensifying ecological soil processes to increase both productivity and sustainability (Figure 1):

(1) a local diagnosis of dysfunctions. This approach requires local action both in the diagnosis and understanding of soil ecological processes and in the deployment of appropriate tools. Indeed, the finalized outcome is contextual and does not tend towards a generality of the practice(s). Local site-specific knowledge is crucial.

(2) a detailed and integrative understanding of soil ecological processes involved in ecosystem functions and related to the dysfunction(s) diagnosed. As ecosystem functions, we refer here to the four aggregated functions proposed by Kibblewhite *et al.*, 2008,

i.e., carbon transformations, nutrient cycling, soil structure maintenance, biological population regulation. These functions aggregate different processes and are at the base of agrosystem services.

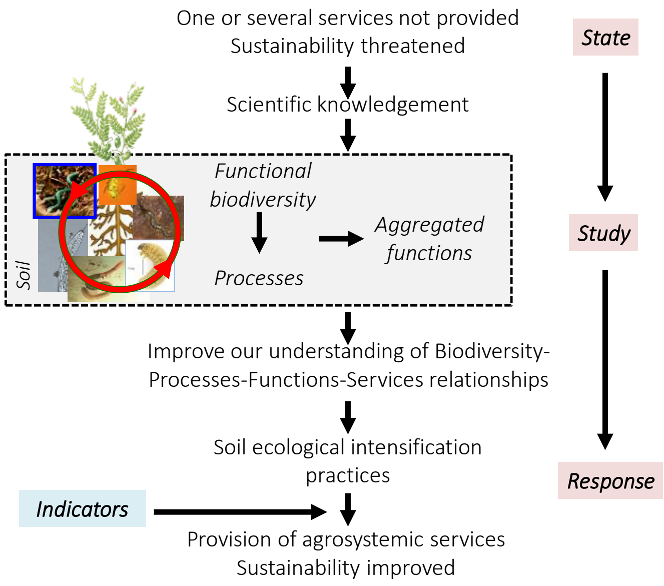

Figure 1: Diagram illustrating the methodological approach allowing to ensure the optimization of soil ecological functions for the sustainable provision of ecosystem services

(3) a co-construction of agricultural practices allowing EISP. The gain of scientific knowledge on the functioning of the soil crossed with the local socio-economic and agronomic constraints is exploited to co-construct innovative alternative agricultural practices. Soil ecological intensification practices are not exclusive of other agroecological practices and require advanced engineering combining several disciplines.

(4) finally, indicators of ecological soil intensification are deployed to measure the effect of practices on long-term ecological processes of the soil. There is a still a huge work to develop relevant indicators of soil processes and a great need of studies to quantify accurately chemical fluxes, to understand biodiversity-processes-functions-services relationships and their drivers, to understand interactions within ecological networks

Results

As results we present here successful case-studies of ecological intensification of soil processes from the tropics. As said above, a non-ecological intensified agricultural use of soils can be faced with one or different dysfunctions, e.g. low fertility, erosion susceptibility, loss of organic matter and/or biodiversity, etc. At some sites, scientists with users developed new, co-constructed, sustainable practices based on a deep knowledge of soil ecological processes.

1- A story of erosion, roots and organic matter. Vertisols from southern Martinique (West Indies) are very prone to erosion due to a high content in sodium. Maintaining high organic matter contents in these soils is the only way to reduce erosion. Scientific studies showed that grass roots such as in pastures have the ability to inject large amounts of carbon in soils and to control erosion (Blanchart *et al.,* 2004).

2- A story of pearl millet cultivars, rhizobacteria and soil aggregation. Soil structural formation is an important driver of soil fertility and depends on root exudation which contributes to soil carbon source and energy supply for microbes. Recent experiment in Senegal studied the plant genetic impact on root exudation and the factors promoting rhizosphere soil aggregation. Results showed that the amount of root-adhering soil per dry mass of root depends on cultivars (Ndour *et al.,* 2017).

3- A story of earthworms, silicon, rice and blast disease. Blast disease is responsible for important global rice production losses leading to high fungicide use. This disease is present in the Highlands of Madagascar and develops mainly after nitrogen fertilization. A recent experiment showed that disease can be controlled by earthworms and silicon (Blanchart *et al.,* 2020). Earthworms have the ability to increase Si availability, as well as P and N availability. Modulation of the expression of plant genes known to be responsive to stress has also been proposed as a mechanism.

4- A story of priming effect, nutrient cycling, organic management and bacteria. Fertilization management in the Highlands of Madagascar is mainly organic. Nevertheless, applications of organic matter can lead to a decrease in soil organic matter through the phenomenon of priming effect by nutrient mining. Recent studies have determined the drivers of this phenomenon, and the microbes involved in it (Razanamalala *et al.,* 2018).

Discussion

Above case-studies show that an ecological intensification of soil processes is possible in order to improve the provision of agrosystem services provided that (i) soil functions and dysfunctions are well described and (ii) innovative practices are co-constructed with users. All above case-studies resulted in propositions of innovative practices:

1- This led to alternative sustainable practices: superficial tillage to avoid organic matter mineralization, temporal rotation or spatial associations of market gardening crops with productive pastures.

2- This study highlighted the need to consider plant breeding to manage carbon content and soil physical characteristics.

3- The innovative practice was a replacement of excessive use of nitrogen fertilizers with agricultural practices involving the development of earthworm populations and coupled with micronutrient fertilization should be developed.

4- This led to the proposition that regular and frequent organic inputs with low C/N ratio (i.e. compost) would be preferable than a unique organic input with high C/N (i.e. residues) at the beginning of the cropping season to maintain carbon and nutrient stocks in soil.

Conclusions

In the context of erosion of global biodiversity, climate change, food security, it appears urgent (i) to improve our understanding of the soil functioning and the determinism of soil functions, (ii) to identify the agronomic levers that make possible to control biotic interactions, and (iii) to evaluate this ecological intensification. This problem-oriented approach proposes nature-based solutions and addresses the complex interactions between Sustainable Development Goals.

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