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Abstract summary

The French Law for the Recovery of Biodiversity, Nature and Landscapes has set a target of reducing the net loss of biodiversity to zero. This biodiversity action plan aims to put this goal into action. One of his aims is to improve our knowledge of soil biodiversity and to develop agricultural and forestry practices that allow it to be conserved restored and developed. This plan can build on several initiatives that were launched since the early 2000's between the French soil science sphere and the French state to improve knowledge on soil biodiversity and to develop indicators relevant for soil quality monitoring and land use decision The implementation in soil monitoring and participatory observatory networks allowed to gain experience on numerous soil types, land uses and agricultural practices and to establish the first reference values e.g. for microbiological characteristics at national scale. The standardisation of protocols, the industrialisation of soil biological analyses, the emergence of advisory services offer based on soil bioindicators allow these tools to be mobilised by the greatest number of soil managers.

Keywords: biodiversity, soil biological indicators, monitoring networks, standardisation, soil management

Introduction, scope and main objectives

Soil health has been defined as the capacity of soil to function as a living system. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots, recycle essential plant nutrients, improve soil structure with positive effects for soil water and nutrient holding capacity, and ultimately improve crop production. A healthy soil also contributes to mitigating climate change by maintaining or increasing its carbon content (FAO, 2015). Hence, as stated by Janez Potocnik in European Commission (2010), "Biodiversity loss and climate change are two of the most pressing challenges of our time, and soil biodiversity is part of the solution to both".

The French Law for the Recovery of Biodiversity, Nature and Landscapes (METS, 2021), published in 2018, has set a target of reducing the net

loss of biodiversity to zero. Acting for the preservation of soil biodiversity is one stake of the French Biodiversity Plan. The implementation of this plan is built on initiatives, launched since the early 2000's to improve knowledge on soil biodiversity and to develop indicators relevant for soil quality monitoring and land use decision.

In this paper, we propose to report these initiatives and their main results. Then, we will discuss how they may contribute to the implementation of the French Biodiversity Plan and draw some perspectives.

Development and testing of soil biological indicators

In the past decades, several calls for research proposals focusing on Ecosystem Services and soil biodiversity were launched by French governmental organisations. In 1998, the French Ministry of Environment has set up the programme "Environmental functions and management of soil heritage" (www.gessol.fr). This programme funded several projects dedicated to the development of soil biological indicators (e.g. Decaëns *et al.*, 2014) and to test their applicability to assess soil functions (e.g. Dubs, 2014). Between 2002 and 2012, the French Agency for Environment and Energy Management (ADEME) co-funded the programme "Bioindicators – biological tools for sustainable soils ", whose objectives were to promote the standardisation of bioindicators to monitor soil quality and to assess the risks for ecosystems and polluted sites. ADEME has published advisory notices on soil bioindicators implementation and recommended key indicators (table 1). Also, the French Ministry of Agriculture (MAA) has published in 2017 an overview of indicators relating to the organic and biological state of soils for farmers (Ministry of the Environment, Energy and The Sea and Ministry of Agriculture, Agri-Food and Forestry, 2017).

In 2018, the French Biodiversity Agency started the research programme "Soil biodiversity and agro-ecology » dedicated to the deciphering of the links between soil management and soil biodiversity. Other national programmes (e.g. SYSTERRA, AgroBiosphere) founded by several research agencies, not directly addressing soil biodiversity, provided relevant knowledge while studying soil contamination or innovative agricultural practices.

At EU level, French laboratories gained expertise and knowledge on the use and interpretation of biological indicators involved in research projects (Envasso, European Commission, 2010b; EcoFinders, European Commission, 2010c; Landmark, European Commission, 2010d).

Table 1: Minimum set of indicators for monitoring agricultural soils (ADEME, 2012)

Monitoring pupose	Indicators	Parameters
Management of sil organic matter	**Micobial**	**Abundance: microbial and fungal biomasses** **Diversity of communities** **Activities: C and N mineralization, ergosterol measurement**

	Fauna	**Abundance and biomass of earthworms** **Functional diversity of nematodes**
Management of agricultural practices	**Microbial**	**Abundance: microbial and fungal biomasses** **Diversity of communities** **Activities: enzymatic measurements linked to C, N, S and P cycles**
	Fauna	**Functional diversity of earthworms and nematodes** **Diversity of collemboal**

Implementation in soil monitoring networks

In 2009 within the FP7 Envasso project it was underlined that biological indicator were missing in quite all EU soil monitoring networks (Morvan *et al.*, 2008) and a list of potential indicators to monitor decline of soil biodiversity was proposed on a tiered approach (Bispo *et al.*, 2009) (Figure 1). Based on the national expertise and the existing protocols, indicators were tested and implemented in the French soil quality monitoring network (RMQS) to spatially assess soil quality across mainland France and overseas territory. Between 2006 and 2012, inventories were conducted at national level, on the soil microbial biomass (Dequiedt *et al.*, 2011) and bacterial communities (e.g. Karimi *et al.*, 2018). At regional scale several biological indicators were also measured (e.g. Ponge *et al.* 2013). A new initiative is underway aiming at inventorying soil microflora and fauna as well as some functional measurements (Imbert *et al.*, 2021) on the RMQS.

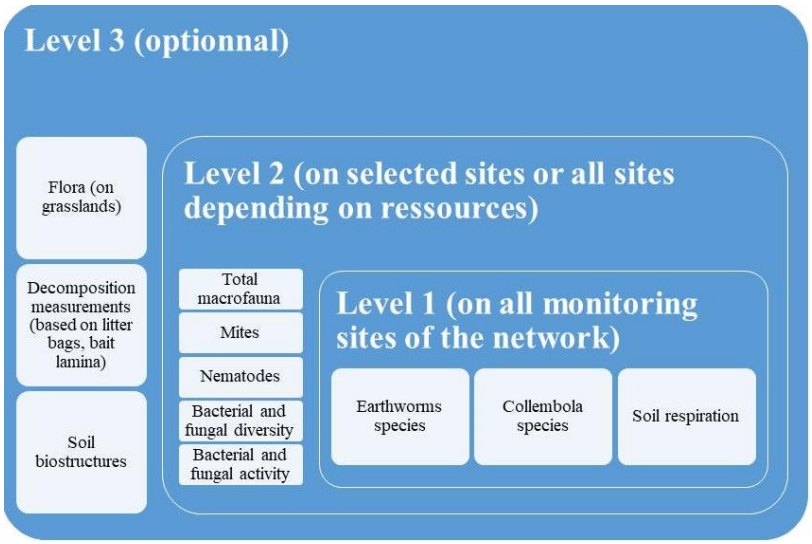

Figure 1: Proposed indicators to monitor soil biodiversity decline in monitoring networks (based on the results of Envasso, see Bispo *et al.*, 2009)

In addition, research organisms have their own long-term monitoring infrastructures (https://www.anaee-france.fr/, IR OZCAR or CA-SYS Agroecology Platform) soil biodiversity are performed on their sites.

During that time, note that participatory observatory networks were also promoted. Volunteer professionals and gardeners are hence encouraged to participate to the observatory programs of earthworms

(OPVT - https://ecobiosoil.univ-rennes1.fr/OPVT_accueil.php) and the agricultural observatory of biodiversity (OAB - http://www.vigienature.fr/fr/agriculteurs). Based on available data, several soil biodiversity indicators are already included in the National Observatory of Biodiversity: earthworms and bacteria.

Transfer through training, standardisation and services offer development

The awareness and training of farmers, agricultural advisers are a key step to consider soil biodiversity. The participatory observatory programmes OPVT and OAB are deploying in training courses of future farmers and agricultural advisers. MAA funded a network about biodiversity and agriculture (http://www.rmt-biodiversite-agriculture.fr/moodle/) with research organisms and different schools of agriculture. The AgrInnov project (2011-2015), funded by MAA and coordinated by INRAE and OFSV (https://www.ofsv.org/), has linked through a participative approach, researcher on soil biological indicators with a network of 250 farmers throughout France. This project has developed and transferred training and dashboard indicators of soil biological quality directly to farmers. The Experimentation and Monitoring Network for Agricultural Innovation takes over from AgrInnov project to train farmers, with the aim of changing their farming systems towards environmental and economic sustainability.

The mobilisation of biological tools as indicators of good soil functioning by agricultural professionals requires also the existence of a supply market to meet the need and also to have protocols that are standardised. ADEME provide financial support to the industrialisation of soil biological analyses and the emergence of advisory services offer based on soil bioindicators for soil managers (agriculture, polluted sites, brownfield management). For instance, the AgroEcoSol project coordinated by the AUREA laboratory aims at developing an advisory service for farmers from 2021 (https://www.ademe.fr/agro-eco-sol).

Soil quality monitoring and development of services offer requires that the methods are widely recognised, reliable, comparable… Standardisation is arguably a best practice. Within the last decade, numerous soil biological indicators were standardised at the international level by the ISO-TC 190 committee (Figure2, from Bispo and Schnebelen, 2018). Also, international standards have been proposed on the basis if methods developed in context of the French research.

The development of an offer also requires being able to interpret the result of a single measurement. Guideline or reference values are needed to statue on the normality of a result (e.g. is the value expected compared to previous measurements or existing knowledge). Considerable databases are needed to do so including biological measurements, but also other factors used to interpret the results as climate, land use, soil type and physico-chemical parameters (Horrigue *et al.*, 2016). As exposed in Figure2, for mainland France, part of the biological indicators already have developed such references (marked "**+**") whereas others are just under development (marked "+/-") or not yet started (marked "-"). All those indicators can be linked

to soil functions which are the way to communicate with land managers and users as farmers (Figure 2).

Group	Indicators	Organisms and/or methods	Standards	Existing references values for France	Link with soil functions
Fauna	Diversity	Earthworms (sampling/extraction)	EN ISO 23611-1	+	Organic matter degradation Biomass production Soil formation Water regulation
		Collembola/mites (sampling/extraction)	EN ISO 23611-2	+/-	Organic matter degradation Biomass production
		Enchytreids (sampling/extraction)	EN ISO 23611-3	-	Organic matter degradation Soil formation
		Nematodes (sampling/extraction)	EN ISO 23611-4	+	Organic matter degradation Biomass production Regulation of pests
		Total macrofauna (sampling/extraction)	EN ISO 23611-5	?	Habitat Organic matter degradation Biomass production Regulation of water and pests
		Fauna (metabarcoding)	-	-	Organic matter degradation Biomass production Regulation of water and pests
	Activity	Bait lamina	EN ISO 18311	-	Organic matter degradation
		Measurement of biostructures	-	-	Soil formation Water regulation Organic matter degradation
Microorganisms	Microbial biomass (based on DNA extraction)	DNA extraction	EN ISO 11 063	+	Organic matter degradation Degradation of contaminants
	Diversity of microbes	PCR analyses based on DNA extraction	ISO 17 601	+	Organic matter degradation Degradation of contaminants
		PLFA analyses	CEN ISO/TS 29843-1 et -2	-	
		Massive sequencing	-	+	
	Global activity	Respiration	NF EN ISO 16072	+	Organic matter degradation Degradation of contaminants
	Enzymatic activities (eg : N, P, S)	Biogeochemical cycles	ISO 14238 ISO/TS 22939 ISO 23753-1 ISO 23753-2	+/-	Organic matter degradation Degradation of contaminants Nutriment cycling

Figure 2: List of indicators with respective methods and standards – links with the soil functions (adapted from Bispo and Schnebellen, 2018)

Discussion and conclusion

The absence of an EU directive on soils leaves a wide range of possibilities to use those works in public policies. The agricultural or forest management practices for the benefit of soil biodiversity and functionality must be encouraged by labels, environmental

certifications, by setting up Payments for Environmental Services (PES), soil diagnostics, or also in the 2nd pillar of the Common Agricultural Policy via Agri-environment-climate Measures. In his action plan for biodiversity, France points at that the "PESs will prioritize the development of practices to preserve soils and restore biodiversity" and the state "will promote soil condition diagnoses that enable purchasers and farmers to benefit from information on the condition of the soils they use in order to put in place appropriate management techniques to the benefit of biodiversity, production quality and the environment."

The different research programmes around soil biology have made it possible to acquire a pool of knowledge that can be mobilized to build tools that are both relevant for the assessment of ecosystem functions and services of soils and which meet the expectations of potential users. The standardisation of the protocols on soil biology quality gives a technical implementation framework. The successful mobilisation outside the scientific sphere will go through the improvement of the interpretation frameworks for farm advisory and the explicit identification of their added values compared to physico-chemical analysis. Moreover, we must keep on efforts in training the agricultural communities. This involves knowledge transfer on bio-indicators, through practical guides, training and decision-support tool but also development of participatory research-action involving the farmers. Finally, raising awareness should not be neglected. The Gessol program has developed in 2010 the Happy Families card games "The hidden life of soils" dedicated to soil biodiversity. This card game has been effective to arouse curiosity among the general public (Antoni *et al.*, 2019). Inspired by the successful Canadian initiative "Soil your undies" and by numerous feedbacks from French farmers, ADEME launched in 2019 a large-scale sensitization campaign named #plantetonslip.

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