iSQAPER
Interactive Soil Quality Assessment

Assessing soil quality in agro-ecosystems

For reversing soil degradation and enhancing soil multifunctionality

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April 2020

The briefing should be cited as follows:
Bongiorno, G., (2020) Assessing soil quality in agro-ecosystems for reversing soil degradation and enhancing soil multifunctionality, Briefing for iSQAPER

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With thanks to reviewers:
Lijbert Brussaard, Else Bünemann-König, Ron de Goede, Luuk Fleskens, Abdallah Alaoui, Gergely Toth, Gottlieb Basch, Coen Ritsema and Catherine Bowyer

Acknowledgements:

This publication is made possible through the iSQAPER research project - Grant Number 63570 (http://www.isqaper-is.eu/) with financial assistance from the European Union.

The authors would like to thank the members of the iSQAPER consortium for their support and interest in this area of research, which inspired making this knowledge more publicly accessible.

CONTENTS

Key messages

Soil performs multiple key functions linked to agricultural productivity and environmental resilience. Land use and soil management affect the soil's ability to contribute to ecosystem services such as food production, water quality and supply, biodiversity protection, and climate regulation, all of which take place within the soil.

The term **soil quality** is used to describe the capacity of soils to perform these multiple functions. Soil quality depends on chemical, physical and biological parameters and can be evaluated by measuring a combination of these parameters, so called '**soil quality indicators**'.

Monitoring soil quality indicators can ultimately help in the establishment of management practices that better support multiple ecosystem services, especially if used in combination and as part of a wider systematic process to drive change and a just transition towards more sustainable production models.

Scientific and technological developments are creating the possibility to deploy novel soil quality indicators that can replace or be combined with existing ones to provide a significantly improved toolbox to monitor soil processes linked to land use and soil management more responsively and effectively. Such information provides decision support to farmers and policy makers on the implementation of alternative and sustainable practices. It also facilitates the understanding of soil quality conditions and the delivery of ecosystem services in the light of policy goals for food security and safety, climate, biodiversity conservation and nutrient management.

For example, the effect of soil management on organic carbon is traditionally measured by monitoring total organic carbon (TOC). However, it can take years for TOC levels to measurably change. The novel indicator permanganate oxidizable carbon (POXC) is a more informative alternative (Bongiorno et al., 2019b). This fraction of TOC is sensitive to management changes in the short term and has been found to be positively related to various chemical, physical and biological parameters associated with soil functioning. Other novel indicators include DNA based methods of sampling biological indicators.

It is essential to define these novel soil quality indicators using standardized protocols, and to make site-specific data that is used to develop them publicly and consistently available. Only with reference values obtained under comparable pedoclimatic and land use conditions, will meaningful results be obtained, which is often not the case.

Measuring and Understanding Soil Quality Indicators for Ecosystem Services

Soil quality is defined as the capacity of a soil to function within ecosystem and land use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1994). Consequently, soils have multiple functions.

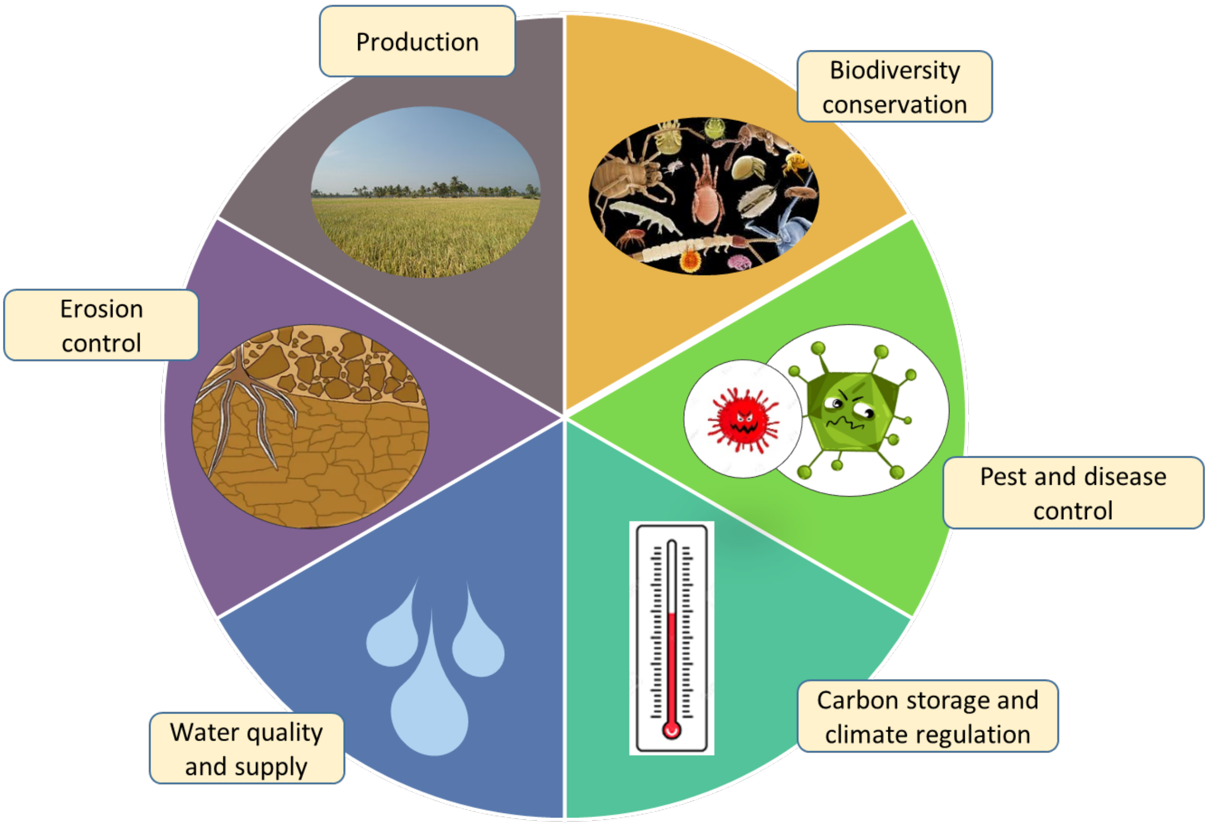


Figure 1. Main soil-mediated ecosystem services derived from agricultural soils as defined in Bünemann et al. (2018).

Soil quality includes both inherent and dynamic soil properties that determine soil processes, and ultimately functionality. Inherent soil properties (e.g. soil texture) are determined by natural soil forming factors, i.e. climate, topography, parent material and time (Jenny, 1941); dynamic soil properties in this context refer to those aspects of soil quality that change as a result of land use and soil management (Schulte et al., 2014).

To understand and predict the effects of soil and land management on ecosystem services, soil chemical, physical and biological properties have to be monitored as 'soil quality indicators'. Soil quality indicators should be related to soil processes and ecosystem services, responsive to management, reproducible, and, preferably, easy to measure at low cost (Bünemann et al., 2018).

The linkage with ecosystem services is essential for policy and management advice (Table 1, based on Bünemann et al., 2018). Since the same soil quality indicators are often linked to multiple soil processes and ecosystem services, it is good practice to measure multiple indicators. This approach is important also for the identification of trade-offs between ecosystem services.

Table 1. The most relevant soil quality indicators for soil-mediated ecosystem services. These indicators are mainly dynamic soil properties that are directly linked to soil and land management. The same indicator can be important for multiple soil-based ecosystem services.

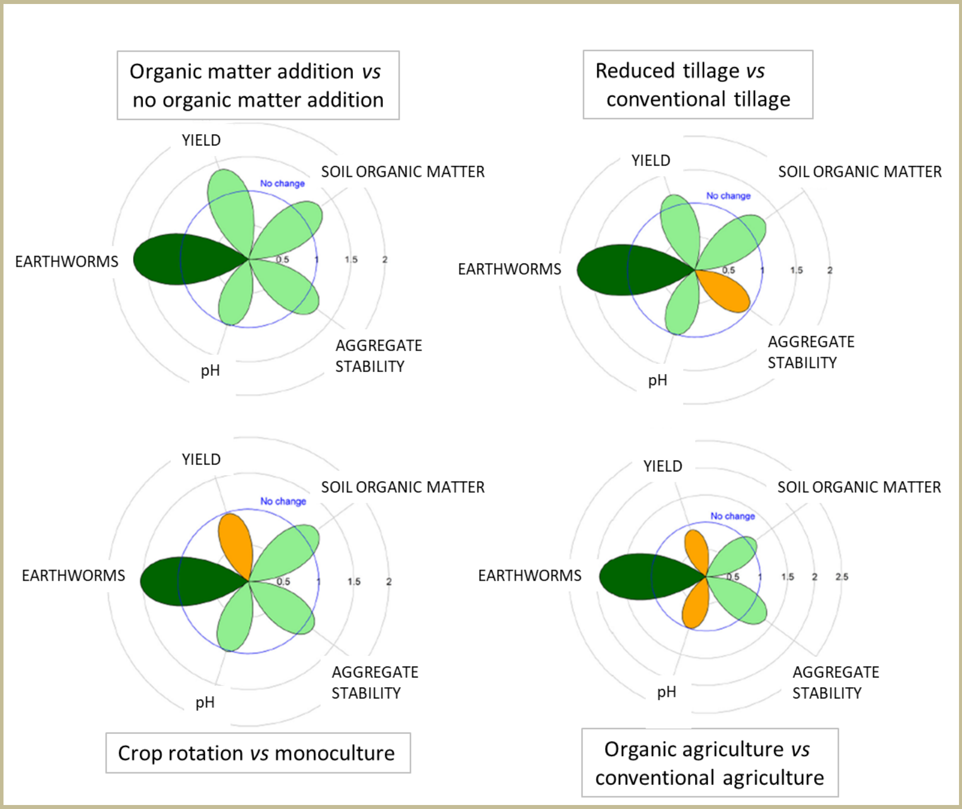
Soil-based ecosystem service	Soil quality indicator	Meaning
Biomass production	Yield	Productivity of the system informing about plant health and problems with nutrients, pathogens
	N mineralization	Capacity of soil organisms to provide N and of plants to obtain N
	Nutrient content (N, P, K, Mg)	Nutrient load available for plants
	pH	Soil acidity determining soil fertility and growth conditions for plants and soil organisms
	Electrical conductivity	Soil salinity determining growth conditions for plants and soil organisms, water quality
	Cation exchange capacity	Capacity of the soil to retain and provide nutrients
	Water holding capacity	Capacity of the soil to retain and provide water
Biodiversity conservation	Number and biomass of earthworms and other micro, macro and meso-fauna groups	Capacity of soil to function as habitat for organisms and sustain biological processes (e.g., decomposition, soil structure formation) associated with ecosystem services

	Microbial biomass C and N	Capacity of soil to function as habitat for organisms and sustain biological processes (e.g., decomposition, nitrogen fixation, population regulation) associated with ecosystem services
	Soil respiration	Capacity of soil to function as habitat for organisms and sustain nutrient cycling
Erosion control	Bulk density	Soil compaction affecting plant and soil organisms growth
	Penetration resistance	Soil compaction affecting plant and organisms growth and water infiltration capacity
	Soil structure and consistency	General soil physical conditions affecting plant and organisms growth and water infiltration capacity
	Slaking test	Susceptibility of soil to disaggregation and erosion
	Soil loss	Susceptibility of soil loss through water and air erosion
	Water-stable aggregates	General soil physical conditions influencing plants and organisms growth, water infiltration and susceptibility to erosion
Pest and disease control	Disease incidence	Presence and virulence of pathogens, and plant susceptibility to disease
	Plant bioassay	Plant disease and capacity of soil to suppress pathogens
Water quality and supply	Water infiltration	Soil water infiltration capacity influencing water and soil loss
	Water holding capacity	Capacity of the soil to retain and provide water
	Hydraulic conductivity	Capacity of the soil to retain and provide water
Climate regulation	Total organic carbon	Carbon storage, water and nutrient retention and habitat for organisms

Land management and land use can disrupt, maintain or improve soil properties such as soil structure, organic carbon content, and biodiversity (Bai et al., 2018) (Box 1). Therefore, the disruption of soil properties can cause a disruption of soil processes and associated ecosystem services.

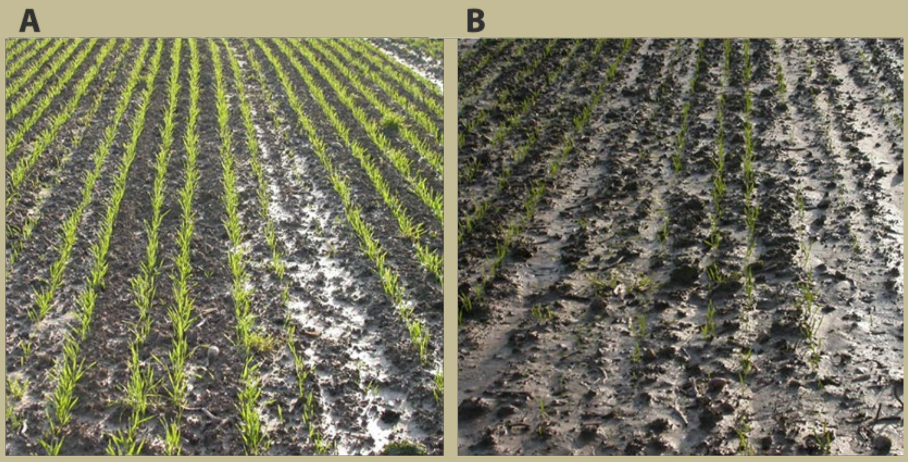
Biomass (food and fibre) production is one of the main services in agro-ecosystems. However, higher agricultural productivity is often achieved by employing management practices that compromise the effective delivery of other ecosystem services important for society at large. It needs to be ensured that soils in agro-ecosystems maintain or increase their capacity to perform ecological functions linked with multiple ecosystem processes and services and not biomass production alone.

Box 1. Understanding the consequences of changes in agricultural land management for soil quality



The flower petals in the figures illustrate the response ratio of five soil quality indicators (yield, soil organic matter, aggregate stability, pH and earthworms) to four alternative vs. standard agricultural management practices. The figures use data from 72 European and Chinese trials and 402 published observations from long-term trials (Bai et al., 2018). Ratios higher than one indicate soil quality improvement (green petals) resulting from the alternative management practice.

Organic matter addition (top left diagram) was positively associated with all soil quality indicators related to ecosystem services such as production (yield), climate regulation (soil organic matter), biodiversity (earthworms), nutrient cycling (pH) and water and erosion control (aggregate stability). Other alternative practices were associated positively with some indicators and negatively or neutrally with others, highlighting the presence of synergies and trade-offs between different soil-based ecosystem services (Sandén et al., 2018). Organic agriculture (bottom right diagram) increased aggregate stability compared to conventional agriculture. In the figure below a visual comparison is shown of the soil surface in winter wheat plots with (A) biodynamic system: addition of composted manure and exclusion of mineral fertilizers and pesticides, and (B) conventional system: only mineral fertilization and addition of pesticides, at the DOK long-term field experiment in Switzerland (Mäder et al., 2002).

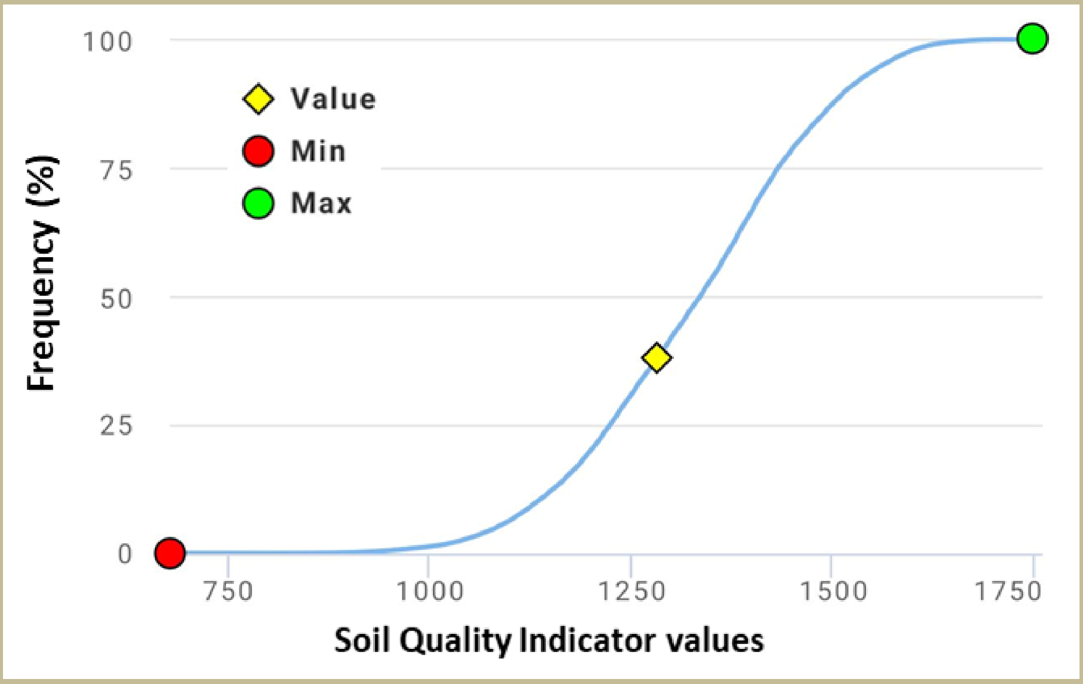


Photos: Fliessbach, November 2020

In photo B, disaggregated soil particles lead to aggregate slaking and consequent surface crusting and smoothing which can increase the risk of wind and water erosion, and nutrient losses. In photo A, earthworm casts, plant roots and soil pores are more frequent, rendering the soil more structured and preventing such problems (Alaoui et al, 2020).

Any indicator must be interpreted and evaluated to understand its meaning regarding the state of a soil and implications for soil management under particular biophysical conditions. To that end, the indicator value can be compared to reference values under natural conditions or under agricultural management with baseline soil characteristics, as in Box 1. Alternatively, indicator values can be compared to given thresholds, as often used in ecotoxicology, or to ranges of values occurring under similar combinations of climatic conditions and soil types, so-called pedoclimatic zones (Box 2). The choice of which approach to adopt depends on the purpose and the setting of the assessment (Alaoui, 2018a). Whichever approach is selected, it is essential to define/establish and monitor soil quality indicators using standardized protocols and make the data publicly and consistently available.

Box 2. Example of the frequency distribution of a certain soil quality indicator in a certain pedoclimatic zone



This graph shows the frequency of a value of a soil quality indicator at a given location (yellow symbol), relative to the frequency of other values of the same indicator measured at other sites in the same pedoclimatic zone. To identify room for improvement, we need to know for each indicator whether ‘more is better’, ‘less is better’, or if there is an optimum value for ecosystem services. Comparative data are essential for scientists to understand soil processes, for advisory services to understand which management options are the best to adopt for supporting wider societal goals in a particular context, and for land managers and farmers to retain the functionality of soil.

Novel Soil Quality Indicators: Supporting Knowledge of Soil Condition

Scientific and technological progress and innovation in soil biology and soil organic carbon research, and rapid developments in methods for measuring soil properties offer new opportunities to monitor changes in soil processes resulting from short and long-term management effects on soils (Bongiorno, 2020). These novel indicators have the potential to be more responsive to the effects of soil management than traditionally measured soil quality indicators. In addition, these developments improve our understanding of the role of biodiversity and carbon in soil processes and ecosystem services and in identifying novel, rapid-to-assess soil quality indicators.

Examples are DNA-based methods that screen the taxonomic and functional genetic potential of soil organisms and spectroscopic techniques that permit high-throughput and cheap screening of thousands of samples. Historically, soil biology has not been included as frequently as physical and chemical indicators in soil quality assessment (Bünemann et al., 2018). This was a consequence of limited knowledge of soil organisms, their complex relationships and the challenges in measuring both the organisms and the processes they perform. However, soil organisms are fundamentally linked to the delivery of soil ecosystem services (Barrios, 2007; de Vries et al., 2013) such as control of erosion (via enhancing soil aggregation) and control of soil pathogens (via antagonistic relationships). Pests and pathogens can also negatively affect plant productivity by feeding on crops. Soil organisms and the biological processes they support are very sensitive to environmental changes brought about by land management (Bastida et al., 2008). For these reasons, biological indicators are particularly useful for soil quality assessment. If integrated with physical and chemical indicators, soil biological indicators will permit sensitive and rapid indication, and hence predictive understanding, of land use and soil management impacts on soils.

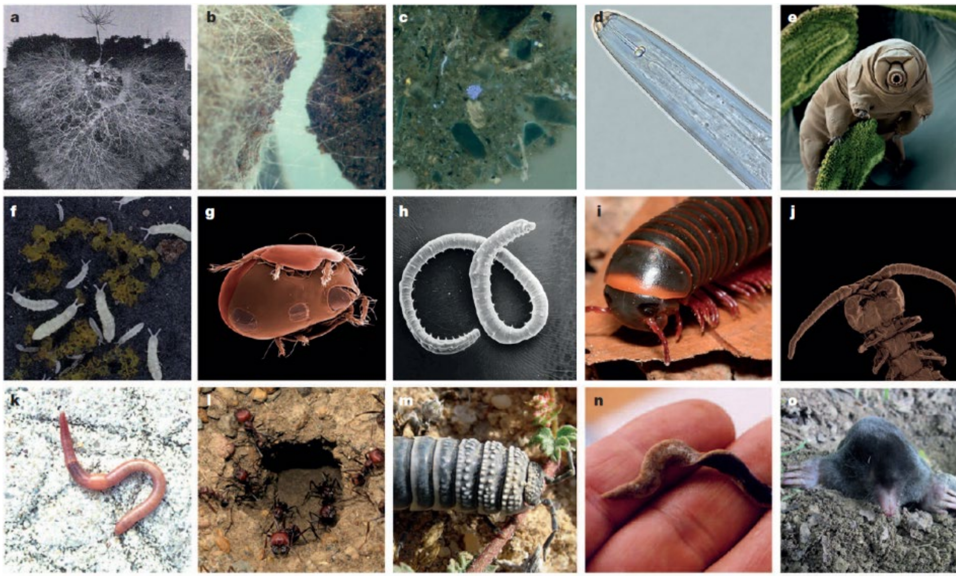


Figure 2. The soil biota, of which some examples are depicted here, has a primary role in soil processes. Technological and knowledge developments in this field of soil science can help in assessing the effects of soil management on ecosystem services (Bardgett and van der Putten, 2014).

Soil Quality Assessment Schemes for Soil Multifunctionality

There is a range of options for science to support and improve the understanding of soil processes and changes and to better inform farmers, farm advisers and policy makers (Figure 3). Scientific recommendations can support a transition toward improved land and soil management that sustains the productive capacity of soils and also delivers multiple ecosystem services providing benefits on farm and to the wider society (such as enhanced water and nutrient cycling, erosion control, and biodiversity conservation). To achieve this there needs to be an integrated approach based on: connectivity between stakeholders; the development of indicators and specifications on how to use and implement them; an understanding of the knowledge gained from data sets and how to interpret this to understand the implications for land use and soil management; a recognition of the need to adapt land use and soil management to take account of soil needs; and ongoing evaluation, adaptation and innovation to improve techniques and ensure they are delivering results expected (as proposed in Figure 3). Within such an approach novel soil quality indicators can be integrated with existing ones to provide a clear set of complementary indicators that provide a full picture of soil multifunctionality as a tool to better support effective land management decisions. In so doing we can support not only the productivity of agricultural land, but agriculture's wider contribution to delivering a just transition to a more sustainable, climate-responsible production model that protects biodiversity and reduces pollution and soil degradation. These indicators can be used as a basis for policy choices, as well as integrated into monitoring of existing measures.

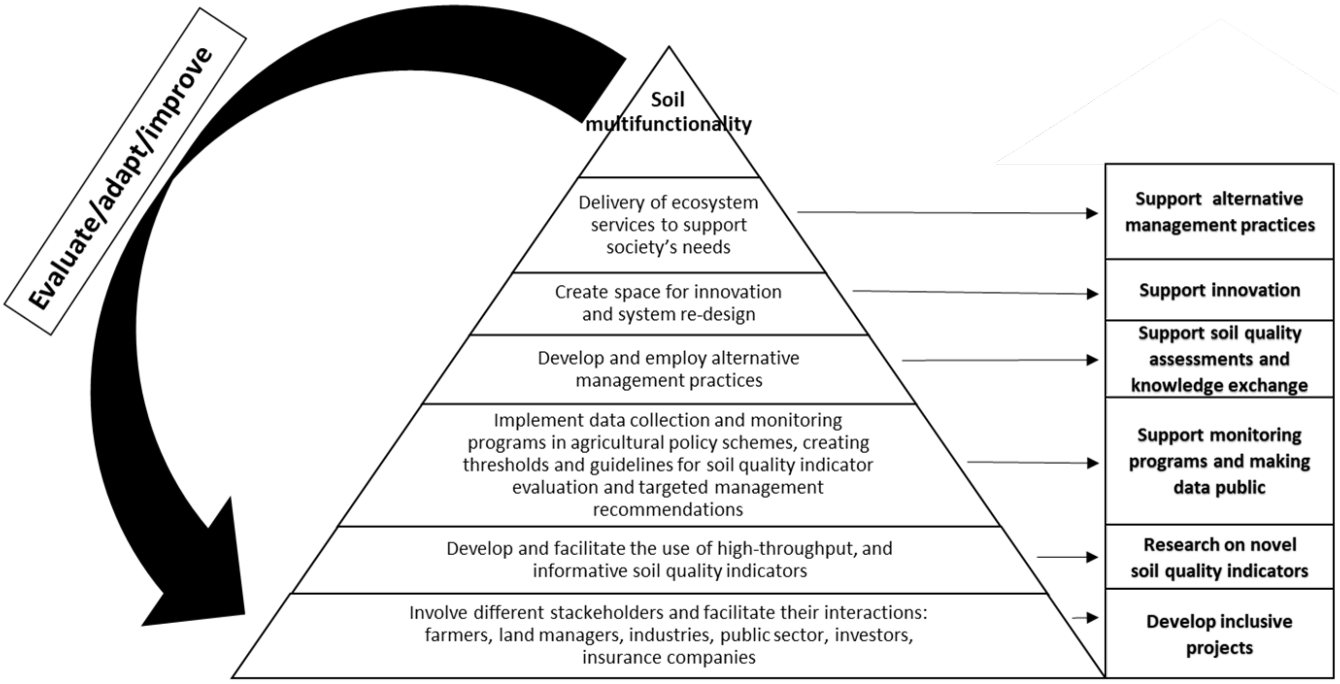


Figure 3. Schematic overview of the opportunities for science, policies and practices to reach soil multifunctionality, and concrete actions that can help in realizing these opportunities.

Science and policy working together: Soil Science Supporting the Understanding of Soil Carbon Emissions and Sequestration

Soil organic carbon is a central soil quality indicator for climate regulation and water and nutrient cycling. Management practices that increase carbon storage should be implemented to enhance the multifunctionality of agricultural soils.

Traditionally, the effect of soil management on organic carbon is measured by monitoring total organic carbon (TOC). However, it can take years for TOC levels to measurably change. The novel indicator permanganate oxidizable carbon (POXC) is a more informative alternative (Bongiorno et al., 2019b). This fraction of TOC is sensitive to management changes in the short term and has been found to be positively related to various chemical, physical and biological parameters associated with soil functioning. For example, POXC is positively connected to the capacity of soils to suppress pathogens (Bongiorno et al., 2019c), to nematode richness and diversity (Bongiorno et al., 2019a) and to microbial activity and functional diversity (Bongiorno et al., 2020. In press).

Novel indicators like POXC improve the understanding of farmers and other land managers of the effects of land management on soil carbon sequestration, soil structure formation and nutrient retention and provision. Monitoring schemes that allow quick evaluation of soil quality improvements due to more sustainable land use and soil management will stimulate sustainable action and contribute to societal objectives.

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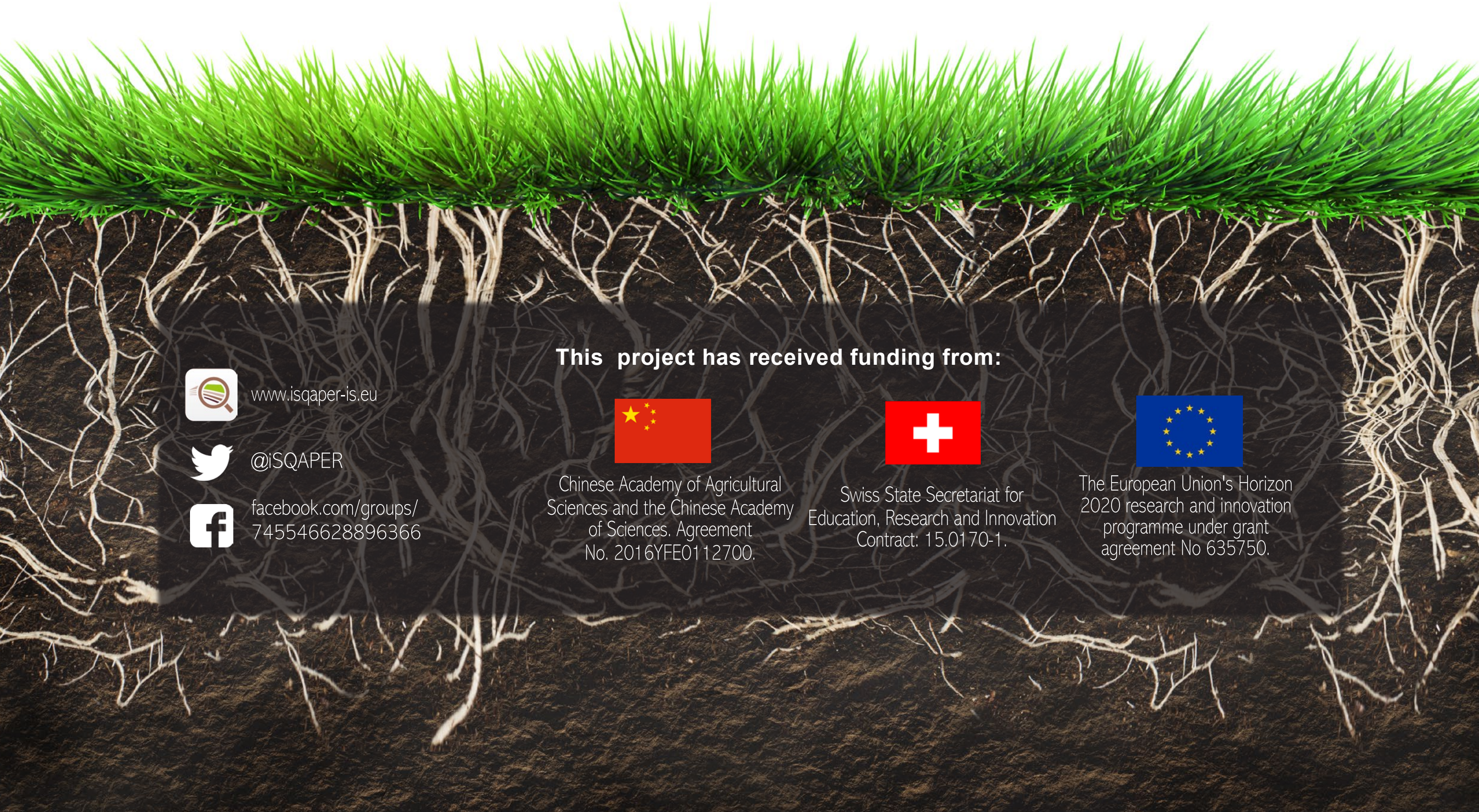

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This project has received funding from:

Chinese Academy of Agricultural Sciences and the Chinese Academy of Sciences. Agreement No. 2016YFE0112700.

Swiss State Secretariat for Education, Research and Innovation Contract: 15.0170-1.

The European Union's Horizon 2020 research and innovation programme under grant agreement No 635750.