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COMMENTARY

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Soil quality and fertility in sustainable agriculture, with a contribution to the biological classification of agricultural soils

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[Correction added on 21 November 2021, after first online publication: Figure 10 and section 6.5 have been removed from this updated version of the article. Subsequent sections have been renumbered. There are additional corrections within this version of the article.]

Abstract

Soils and crops are particularly vulnerable to climate change and environmental stresses. In many agrosystems, soil biodiversity and ecosystem services provided by soils are under threat from a range of natural and human drivers. Agricultural soils are often subject to agronomic practices that disrupt soil trophic networks and make soils less productive in the long term. In this scenario, sustainable soil use aimed at improving plant/root status, growth and development plays a crucial role for enhancing the biological capacity of agricultural soils. This commentary paper is divided into the following four main sections: (i) the contentious nature of soil organic matter; (ii) soil biological quality/fertility; (iii) soil classification; and, (iv) which agricultural practices can be defined as sustainable? The published literature was analyzed within a holistic framework, with agrosystems considered as living systems where soil, vegetation, fauna and microorganisms co-evolve and are reciprocally influenced. Ultimately, this article will suggest a better stewardship of agricultural soils as a natural capital.

KEYWORDS

conservation and sustainable agriculture, humus, plant–microorganisms–soil interactions, soil classification, soil ecology, soil organic matter, soil quality and fertility

1 | INTRODUCTION

Soils are one of our most valuable resources and are fundamental natural capitals at the base of all trophic chains. In agricultural systems, management practices that ensure high production often have negative repercussions on soil health, quality and fertility (Figure 1). A high number of physicochemical, microbiological and biochemical parameters are responsible for the fertility of a soil (Cheik & Jouquet, 2020; Jiang et al., 2020). However, because of the challenge of considering them altogether, it is inevitable to select the most informative and reliable ones. Soil biological properties are very sensitive to small-scale changes occurring in a soil, compared to soil physicochemical parameters. To ensure the long-term sustainability of cropping systems, both the status of soil organisms and crops need to be taken into account (Pelosi & Römbke, 2018; de Vries & Wallenstein, 2017). In this paper, the specific biological indicators of soil health will be discussed together with soil physicochemical parameters and suggestions for soil classification. The core assumption is that healthy soils provide an optimal environment for soil organisms that stimulates plant physiological and biochemical responses to stress (Pinstrup-Andersen & Pandya-Lorch, 1998;

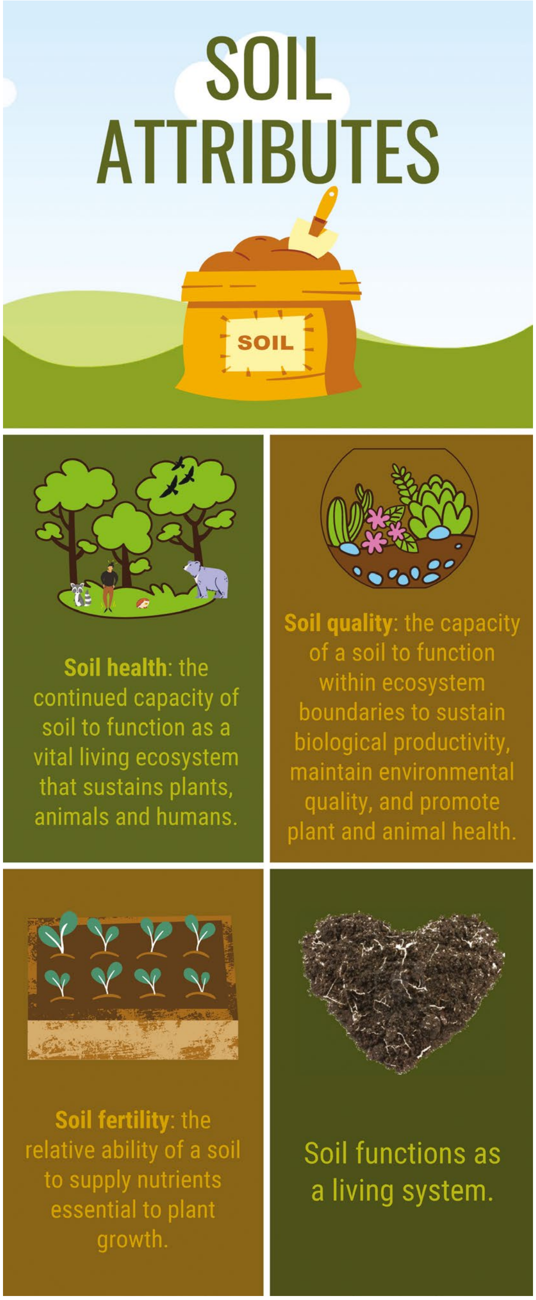

FIGURE 1 The three key attributes of soil, considered as a living system

Soussana et al., 2019). The overall message is the urgency of better understanding the effects of soil management practices on the structure of soil microbial and animal communities and on plant health and production. The selection of biological indicators closely related to soil microbial dynamics could be essential for the quantification of soil quality and its resilience to stresses, two basic requisites of soil fertility. The indicators adopted could provide reliable and easy-to-interpret information on soil and plant status, as they are little affected by the fluctuations related to the season and the topographic effects. Carrying out a representative soil sampling, measuring soil biological indicators, proposing a correct soil classification and integrating all data in a holistic framework can facilitate the inclusion of soil health, quality and fertility in management decisions made by farmers, land managers and crop advisers.

Healthy soils provide an environment for soil organisms and plants that minimizes stresses. The latter can be quantified with biological indicators (Duru et al., 2015; Hopkin, 2008; Schloter et al., 2018; Vogel et al., 2018). A high number of physicochemical, biological and biochemical parameters are responsible for the fertility of a soil. However, due to the impossibility of considering all of them, it is inevitable to select the most informative and reliable ones (Gil-Sotres et al., 2005). Generally, the physicochemical parameters are of scarce utility as indicators, as they are altered often when soils are subjected to drastic disturbances (Filip, 2002). On the other side, some soil biochemical properties are sensitive to smaller changes occurring in a soil (Muscolo et al., 2015; Wallenstein & Vilgalys, 2005; Yakovchenko et al., 1996). These indicators should be a measure that provides reliable and easy-to-interpret information and they should not be affected by the fluctuations related to the season and the positional effect, because this could prevent the identification of changes because of perturbations, damages or environmental stresses (Arshad & Martin, 2002). Moreover, to have a clear picture, soil indicators should be combined with plant indicators of stress (Veen et al., 2019). Understanding the effects of agricultural management practices on soil health, soil microorganisms/animals and plants is important, but soil health should be included as a factor when management decisions are made by farmers, land managers and crop advisers.

Despite significant data gaps, there is growing evidence that unsustainable agricultural practices not only negatively affect the health and quality of the soils needed to sustain healthy crops and provide nutrient-rich foods, but they can also significantly affect the integrity and resilience of the ecosystem as a whole. To 'break' the above-cited vicious circle, sustainable solutions are required to facilitate the conservation of soils. But, in order to understand which soils are or can be sustainably managed, the criteria of soil classification are essential. The founders of the soil classification had linked the different units to precise pedogenetic processes (FAO-UNESCO, 1974) to be able to define the functioning of each unit. The advantages of knowing the position of a cultivated field on the map of the distribution of the world's soils remain minimal for the farmer. Scale and micro-morphological or purely local factors intervene and affect the functionality of the soil map. Generally, farmers do not know the name of the soils they are cultivating. Not even many scientists who study natural ecosystems know the name of the soils in which they grow plants or raise cattle. In the laboratory, for example, when experimenting on different plants to know their ability to grow or produce, no one ever imagined that soil could exist as a real living, interacting complete (and quite independent) system.

This article is focused on the most advanced and updated research on the processes occurring at the interface between soil physicochemical aspects, plant roots and soil microorganisms/animals in sustainable agrosystems, and on the practices and ways to establish sustainable soils and preserve their fertility. The analysis of published literature highlighted that:

1. soil humus formation, soil compaction and degradation, soil–plant–atmosphere interactions, root development and rhizosphere processes, vegetation types and phytosociology, signalling among plants and organisms, and plant nutrient balance have all crucial roles in making a soil really sustainable (paragraphs 2 and 3);
2. a conspicuous part of soil physical, chemical and biological fertility in agroecosystems can be attributed to the action of soil microorganisms, with a substantial contribution of soil animals (paragraph 4);
3. a new paradigm for soil classification is nowadays necessary for creating the conditions for soils to be sustainable and able to provide ecosystem services (paragraph 5).

In this article, all these aspects are considered in a holistic view, where agrosystems are considered as living system where soil, vegetation, fauna and microorganisms co-evolve and are reciprocally influenced (paragraph 6). In living soils, the key role of microorganisms in agrosystems should be seriously taken into account in land management strategies, focusing not exclusively on crop yield and quality, but also on soil fertility restoration and environmental safety. Moreover, the role of soil fauna, especially considering their interactions with microorganisms and plant roots, can surely contribute to the long-term sustainability of agricultural soils.

On this basis, the aim of this paper is to reveal the complex interactions between soil physical and chemical properties (on which classification is mainly based), soil microbial diversity and plant health in sustainable agroecosystems (crop soils). Nowadays, agricultural activity, rather than considering just productivity, is focused on the quality of products, natural resource stewardship and environmental aspects, moving towards sustainable management techniques. The sustainable, judicious and efficient use of soils is thus essential to support continued agricultural production and quality. Focusing on sustainable soil use management and food production, this new type of agriculture can perfectly fit within the background of natural resources challenge, where positive mutual interactions between soil microorganisms and cultivated plants play a key role.

2 | THE CONTENTIOUS NATURE OF SOIL ORGANIC MATTER

Lehmann and Kleber (2015) reject the concept of humus and claim that: 'Government-funded research programs must therefore preferentially support science that bridges the gap between detailed and fine-scale mechanistic research at the plant-soil interface and field-scale research relevant to those who manage soils for their multiple ecosystem services'. In their 'Soil continuum model – Consolidated view' (Figure 2), they replaced 'humification' and 'mineralization' with the less precise terms of 'formation' and 'destruction'. Stevenson (1994),[1] quoted in their article, founded the organic matter science accurately describing large to small molecules and their specific properties in a model very similar to the one presented as a novelty by Lehman and Kleber. With the intention of strengthening our position in defence of humus, we report in Appendix S1 the astonishing Outlook of another book (Waksman, 1936) that Lehmann and Kleber (2015) cite as 'The first major critique of the humification concept'. It seems to us instead that this brilliant scientist predicted soil depletion as a consequence of denying the concept of 'Humus as an organic system'.

As for 'fine-scale mechanistic research', it reminds us of those who would like to eat the pills that astronauts carry into space, instead of real legumes or cooked meats. Then maybe they complain that they are not so healthy. Atoms make up the brain, but thoughts come from the combination of so much knowledge that alone it gushes out and establishes alternative paths, which are construction, not simple mechanical movements of electrons.

3 | SOIL PHYSICOCHEMICAL QUALITY AND CHANGES IN SOIL ORGANIC MATTER

One of the main worldwide agricultural problems is the decline in soil fertility, mainly due to the reduction of soil biodiversity, and of nutrient and water content.

[1][Correction added on 21 November 2021, after first online publication: Stevenson et al. (2020) has been changed to Stevenson 1994. The reference section has been amended to reflect this change.]

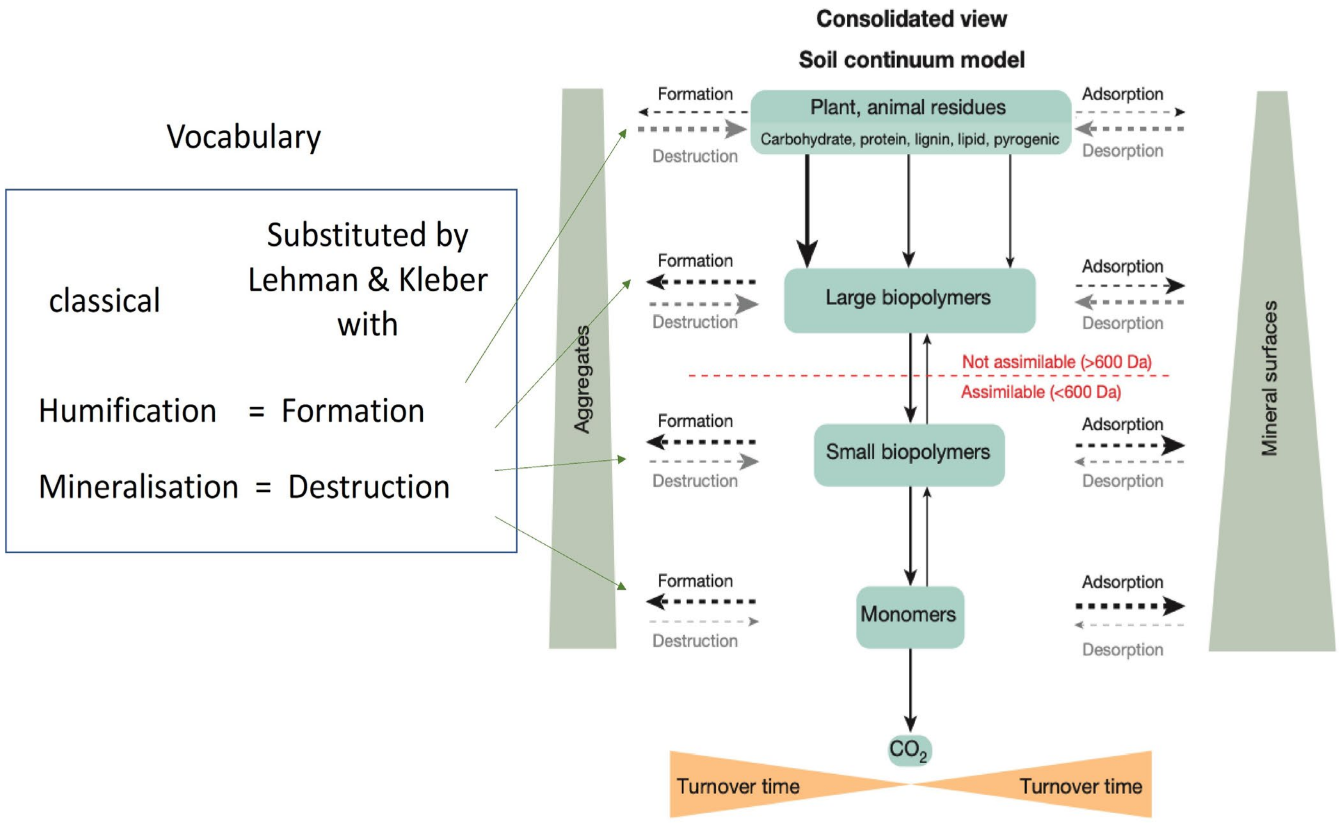

FIGURE 2 From 'The contentious nature of soil organic matter'. Figure entitled: Reconciliation of current conceptual models for the fate of organic debris into a consolidated view of organic matter cycles and ecosystem controls in soil (Lehmann & Kleber, 2015)

Agricultural soils are particularly susceptible to this problem, as they are based on the purposed simplification of the relationships between the plant and other components of the natural habitat. This simplification should make agricultural ecosystems easier to be controlled, but it creates conditions of extreme weakness for plant life and, in fact, is nothing else than a dream. Many studies have shown that the conversion of natural land to agriculture, together with the agricultural intensification that enhances soil organic matter (SOM) depletion, makes the greatest contribution to soil biodiversity loss (Giller et al., 1997; Six et al., 2004; Sofo et al., 2014, 2020; Vitti et al., 2015). The large-scale use of pesticides may also have direct or indirect effects on soil biodiversity, but the lack of data has resulted in contradictory research results (EASAC, 2018; Silva et al., 2019). SOM, especially its stabilized fraction (humus in chemical sense), plays a crucial role in climate change mitigation and adaptation (IPCC, 2019). Amount and types of SOM are principally determined by the continuous physical and chemical action of soil organisms. Soil fauna and microbes are crucial for shredding, transforming and decomposing SOM (Filser et al., 2016). For this reason, studies focused on understanding soil microorganisms-SOM and macrofauna-SOM interactions are needed, and guidelines for future experimentation and best regenerative practices to exploit soil multifunctionality have to be developed, tested and validated.

Soils and crops are vulnerable to climate change and environmental stress, and they will be more and more in the next future. Many crops are endangered by increasing water shortage, often due to changes in rainfall frequency, and rise of soil aridity and desertification, eventually resulting in deteriorated soil structure and critically low levels of SOM, macro- and micronutrients, all of which essential for water provision and plant growth (Matson et al., 1997; Sofo et al., 2019a). The frequent and strong soil tillage, typical of intensive agriculture, significantly affects the stability of soil microaggregates that have a key role in SOM stabilization and support long-term carbon sequestration, being more stable than macroaggregates (Filser et al., 2016). This triggers a detrimental vicious circle which ultimately leads to an increase in the use of mineral fertilizers and pesticides, and needs continuous and strong soil tillage to replace the burrowing and aggregating activity of soil animals, again increasing SOM loss (Silva et al., 2019). In brief, such soils become mere 'containers' for plant roots and function as a carbon source, worsening the greenhouse effect even further.

Healthy, fertile soils are rich in SOM built of carbon that living plants remove from the atmosphere through photosynthesis. SOM fuels the soil organisms which improve soil structure and recycle mineral elements that plants take up as nutrients (FAO, 2015, 2017). But soils release carbon, too. The frequent use of tillage and fertilizers, characteristic of modern conventional agriculture, has accelerated SOM degradation, releasing more carbon into the atmosphere. The last IPCC report (IPCC, 2019) concludes that, globally, cropland soils have lost 20 per cent to 60 per cent of their original SOM content. On top of those losses, modern agriculture consumes a lot of fossil fuels to pull ploughs and manufacture the synthetic nitrogen fertilizers that farmers rely on to coax large harvests from degraded soils. Additionally, restoring soil health would help mitigate the effects of climate change. Increasing the amount of SOM enhances its ability to hold water. Improving soil structure would reduce erosion and retain more rainfall, where it can better sustain crops—especially during drought-stressed years (Sofo et al., 2019a). In addition to benefiting the climate, less fertilizer use will reduce off-farm water pollution (Silva et al., 2019). Land management choices also affect the amount of carbon stored in trees, plants and soil (FAO, 2018). The last IPCC report (IPCC, 2019) estimates that serious changes in forestry and agriculture to curtail deforestation and improve soil management could reduce global emissions by 5–20%. While this would not solve the climate problem, it would represent a significant down payment on a global solution.

What is really important to monitor in a soil? For sure, a comprehensive analysis and in-depth analysis of soil characteristics. For doing this, a correct soil sampling (e.g., by analysing of composite soil samples taken at different soil depths) and/or an appropriate pedological excavation are essential. This can allow the definition of physical soil properties (accumulation of salts, soil compaction, reduction of macropores, soil hydraulic conductivity – vertical and horizontal water infiltration), soil macroporosity (with macropores analysis and their shape and size, both relevant for water infiltration), soil moisture, preferably measured by sensors at different soil depths during the year. Other important parameters for defining soil fertility are the root status, evaluation of the healthy status of the roots and of root morphology (root density, root diameter, amount of white, suberized and dead roots, etc.), microscopic analysis of the roots to observe eventual physical damage of the roots (e.g., necrotic parts, increased lignification, etc.). Soil gas analyses are also relevant, as the determination of CO_2, NO_x and CH_4 (and O_2 too, even if it cannot be easily detected) by means of GS-chromatographic techniques or portable laser-based trace gas analyzers. This will allow to distinguish between anaerobic and aerobic micro-environments, with these latter able to promote several plant diseases due to pathogenic microbial attacks.

4 | SOIL BIOLOGICAL QUALITY/ FERTILITY

Agricultural soils are a natural capital of enormous importance that provides the foundation for food production and, in terms of the human lifespan, are not a renewable resource. For this reason, they must be preserved for the future. Soils host a quarter of our planet's biodiversity, but most of it remains unknown (Antonelli et al., 2020; Fierer, 2017; Sofo et al., 2010, 2020; Wall et al., 2010). One gram of soil may contain up to one billion bacterial cells, tens of thousands of taxa, up to 200 million of fungal hyphae, and a wide range of invertebrates like earthworms, springtails and nematodes (Wagg et al., 2014), that are all part of a complex and interconnected food web (Lavelle et al., 2014; Wall et al., 2015; Williamson et al., 2017). The health of all multicellular organisms (including plants, animals, and humans) and their surrounding ecosystems are interconnected through a subset of microbial organisms found in the plant and soil compartments, particularly in the rhizosphere. Plants nurture an entire world of soil organisms that feed and protect the plants according to aboveground–belowground, plant–soil feedbacks (PSFs) that have different spatio-temporal scales and are greatly affected by climate-related factors (Ponge, 2013; Veen et al., 2019).

The diverse communities of telluric bacteria and fungi keep the soil healthy and fertile and determine the main biogeochemical processes that make life possible on Earth (Dastgerdi et al., 2020; Sweeney et al., 2020; Wilpiszeski et al., 2019). They play fundamental roles in driving many ecosystem processes on which the functioning of terrestrial ecosystems depends on, including soil formation, nutrient and water cycling, climate regulation, carbon storage, production of food, medicine and fibre, disease and pest control, and greater resilience to global change (Bardgett & Van Der Putten, 2014). While soil biodiversity represents an important biological and genetic resource for biotechnological innovation with benefits to society, it is increasingly threatened by different forms of land degradation (FAO, 2015; FAO, 2017). Soil biodiversity is vulnerable to many human disturbances, including intensive and non-sustainable agricultural practices, land use, climate change, nitrogen enrichment, soil pollution, invasive species and sealing of soil (Orgiazzi et al., 2015). Soil microorganisms' dynamics (e.g. mobility, growth, nutrient absorption and respiration), mainly responsible for soil fertility and quality (Bünemann et al., 2018), are strongly affected by the soil management (Enwall et al., 2007; Jeanbille et al., 2016; Sofo et al., 2020a). When the soil microbial biocoenosis is significantly altered, cultivated plants are more susceptible to diseases and display stunted growth. In this view, correct agronomic techniques (fertilization, irrigation, soil tillage, etc.) become instruments to recover the disrupted equilibrium. However, the functionality and metabolism of soil microorganisms are related to soil quality and fertility, as they influence and, at the same time, are influenced by the soil C and N contents, bacteria being an essential part of C and N cycling processes (de Vries & Shade, 2013; Li et al., 2018; Mooshammer et al., 2014; de Vries & Wallenstein, 2017). Microbial interactions play a critical role not only in regulating ecological functions and processes but ultimately in determining the health of plants, animals and humans as components of terrestrial ecosystems (Fierer, 2017; Sofo et al., 2020b; Stevenson, 1994). Having co-evolved with a plethora of microorganisms, plants benefit from microbial symbiosis, while simultaneously facing challenges from pathogens.

Microbial communities are regulated by the activity of soil animals, among which ecosystem engineers play an essential role (Lavelle, 2002). Earthworms, ants and termites (in arid tropical countries) contribute significantly to the creation of an interconnected pore network (Pagenkemper et al., 2015) into which air and water are circulating (Pla et al., 2017), and which are hot spots of microbial activity (Hoang et al., 2016). They also contribute to the creation of soil aggregates (Lavelle et al., 2020), offering a dynamic habitat to microbial colonies (Gupta & Germida, 2015) and preventing loss of carbon, water and nutrients (Pulleman & Marinissen, 2004). Soil engineers and their associated microbiome produce metabolites which exert a hormonal effect on plants (Muscolo et al., 1996) and act as signals which stimulate the defence metabolism of plants (Blouin et al., 2005). Soil animals of smaller size, although not directly involved in the physical transformation of the soil, are the main regulating agents of the microbial compartment. By feeding on fungi and bacteria, they contribute to maintain the microbial biomass in an active state (Kaneda & Kaneko, 2008), decrease competition among microbial strains by feeding preferentially on those growing faster (Newell, 1984). Although still in need of research, it can be expected that selective grazing of microbial colonies by tiny soil animals (nematodes, protozoa, microarthropods, enchytraeids) increases soil microbial biodiversity locally, as this has been repetitively shown to occur with grassland vegetation under moderate herbivore grazing (review in Metera et al., 2010). It has even been suggested that some soil animals would consume preferentially microbial pathogens and thus could contribute to decrease soil pathogenicity (Friberg et al., 2005). Soil food webs, from microbes to top predators, include trophic chains (Pollierer et al., 2019) by which fresh organic matter is transformed in humus (Lehmann & Kleber, 2015), and that at a rate increasing with number and complementary of functional niches of soil animals (Heemsbergen et al., 2004).

It is essential to link biodiversity measures with specific soil functions and plant status under particular environmental contexts, particularly in agrosystems (Ramirez et al., 2015). For instance, while some soil functions are driven by a diverse set of organisms that contribute to functional resilience (e.g., decomposition), other soil functions involve a more specific set of organisms (e.g., nitrifiers, biocontrol agents) which make them more vulnerable to biodiversity loss. (Wagg et al., 2014) showed that soil biodiversity loss or simplification of soil community composition can impair multiple ecosystem functions, including plant diversity, decomposition, nutrient retention and nutrient cycling. A better understanding of the pivotal roles of soil organisms in mediating soil-based ecosystem services, as affected by ecosystem management approaches and practices adapted to socio-ecological contexts, is also central to guiding biodiversity-friendly agricultural intensification trajectories (Barrios, 2007; FAO, 2018).

5 | SOIL CLASSIFICATION

5.1 | Crucial historical legacies

Before moving on to a new proposal of soil classification, let's summarize the crucial historical legacies of two masters of soil classification, Dukuchaev Vasily Vasilyevich (1846–1903), considered the founder of the soil classification in Europe, and Hans Jenny (1899–1992), one of the greatest American pedologists, a Swiss who ended up working in California at Berkeley University.

1. From Zones verticales des sols, zones agricoles, sols du Caucase' (Dokuchaev, 1900), cited by Jean-Paul Legros in 'A l'aube de la Science du sol' (Legros, 2019):
   a. Climate, biological agents, rock, topography and duration are the factors of soil differentiation, or the factors of pedogenesis.
   b. Climate and corresponding vegetation are the main ones responsible for the organization of soils on a global scale.
   c. At the field scale, climatic variability does not have to be considered while topography and variability of the geological substrate can still modify soils.
   d. Dokuchaev and his students had also observed that there were exceptions to the climate zonality. Locally,

this or that environmental factor plays a preponderant role and masks the role of climate. It will take many years to conceptually resolve this problem, as evidenced by the changes in vocabulary introduced on the subject over time. All the reflections carried out lead us to distinguishing between 'zonal' soils that are part of the climatic zonality, 'azonal' soils, whenever the rock outcrops directly, and 'intrazonal' soils, whose characteristics are linked to special conditions, such as excess water or salt.

2. In 'Factors of soil formation - A System of Quantitative Pedology' (Jenny, 1941):
   a. The soil system is an open system; substances may be added to or removed from it. Every system is characterized by properties that we may designate by symbols, such as s1, s2, s3, s4, s5, etc. For example, s1 may indicate nitrogen content, s2 acidity, s3 apparent density, s4 amount of calcium, s5 pressure of carbon dioxide, etc. Any system is defined when its properties are stated.
   b. The initial state of the soil system has been designated as parent material. Climate (*cl*), Organisms (*o*), Topography (*r*), Parent material (*p*) and Time (*t*) completely describe the soil system. The total change of any soil property depends on all the changes of the soil-forming factors following a fundamental equation: $s = f\,(cl, o, r, p, t, \bullet\bullet\bullet)$, where: *s* stands for 'soil property', *f* for 'function of', or 'dependent on', dots show that, besides the variables listed, additional soil formers may have to be included. In a more precise differential mathematical formula, the equation becomes: $ds = \left(\frac{\partial s}{\partial cl}\right)_{o,r,p,t^{dcl}} + \left(\frac{\partial s}{\partial o}\right)_{cl,r,p,t^{do}} + \left(\frac{\partial s}{\partial cl}\right)_{cl,p,p,t^{dt}} \left(\frac{\partial s}{\partial p}\right)_{cl,o,r,t^{dp}} \left(\frac{\partial s}{\partial cl}\right)_{cl,o,r,p^{dt}}$
   c. In selecting *cl, o, r, p* and *t* as the independent variables of the soil system, we do not assert that these factors never enter functional relationships among themselves. We emphasize the fact that the soil formers may vary independently and may be obtained in a great variety of constellations, either in nature or under experimental conditions. To find out the role played by each soil-forming factor, it is necessary that all the remaining factors be kept constant. A serious practical difficulty in solving $s = f\,(cl, o, r, p, t, \bullet\bullet\bullet)$ in the field arises from the requirement of keeping the soil formers constant. In laboratory experiments on soil formation, we can exercise rigid control of the conditioning variables (e.g., temperature, moisture, etc.) and thus obtain sets of data that leave no doubt as to the functional relationship between them. Under field conditions, considerable variation in the magnitude of the variables cannot be avoided, in consequence of which we arrive at scatter diagrams rather than perfect functions. Statistical considerations must be introduced, and the resulting equations possess the character of general trends only. Even so, the gain in scientific knowledge fully justifies the mode of approach.

5.2 | Soil and vegetation

We know colleagues who attempted to classify soil referring to soil classification manuals (national and international issues). For being sure whether their classification was right, they always had to ask a specialist intervention, and many times, they were wrong with some parameters and names. This does not surprise us: soil is a very complex part of an ecosystem. But there must be means of making it accessible to everyone. Although not quite completely, botanists have made themselves understand when classifying vegetation.[2] There are several aspects that vegetation and soil coverings have in common:

1. both are 'covers', both correspond to a continuous layer that shows changes inside and outside perceptible to the human eye. If there is more water in the system, for example, the vegetation changes and also the underlying soil; external change can also be seen from satellite; the internal change (structure) is noticed by the naked eye with some training. Of course, the more the water (or other main ecological factors) balance differs, the more the change is visible;
2. in both, the whole cover can be broken down into sub-layers. For example, for vegetation we speak of arboreal, shrubby and herbaceous layers; for the soil of organic, organic-mineral and mineral horizons;
3. in both cases, circumscribing spatial sub-units (horizontal or vertical) is not so simple, because the transition from one to the other unit is rarely abrupt; very often it is gradual and nuanced. It is normal for this to happen, because in the two cases, the factors involved in the distribution of the plant and animal species that inhabit these two coverages are manifold, interdependent and evolving.

We know that using the characteristic species of the phytosociological units to map the forest vegetation, the part of the forest occupied by undefined vegetation types becomes larger than that occupied by known vegetation types (Zanella, 1993, 1998; Zanella et al., 1994). In fact, to define vegetation units, lists of particular species are needed; these characteristic species are not the most

[2][Correction added on 21 November 2021, after first online publication: A section of text at the beginning of section 5.2 has been deleted. Column 1, Lines 1-7, "study forest ecosystems ... We have already discussed with them: they".]

common in each vegetation unit (if they were the most common, they would also be present elsewhere). Thus, by definition, a large part of an area covered by phytosociological units lacks of characteristic species. This prevents phytosociology from best expressing its operationality. A map of the distribution of vegetation units is always ambiguous and nuanced in many transitional places (Bartoli, 1966; Susmel, 1959, 1980). The founding principle (Braun-Blanquet, 1964; Clements, 1936) says that the species lists are repetitive in the space, and therefore, it is possible to put a name on each list and produce vegetation maps. We know, however, that for ecological reasons, plant lists can only be partially repetitive. The species respond to the environment and form an invaluable number of combinations that are constantly evolving in space and time; they follow the local becoming of every area of fractal size on planet Earth. To establish the composition of the phytosociological units, people use multivariate statistical analysis programs. Depending on the number of surveys, the locations chosen for the investigation and the temporal period in which the counting of the species is carried out, the result changes (Zanella, 1990).

On the phytosociological side, however, the observation remains that we could not do better: the best vegetation maps are the phytosociological ones. This is possible because the phytosociological surveys are carried out within 'ecologically homogeneous' areas. To make a survey, people do not have to choose a random point, but to place themselves in the centre of an ecologically homogeneous environment. At the International Station of Phytosociology of Bailleul (France), we discussed this aspect many times with professor Jean-Marie Géhu, the heir of the works of Braun-Balquet. It was his main fundamental, unforgettable teaching. 'Keep this principle in mind, never give it up, you seem to be wasting time, but you are gaining a lot of it: choose carefully the environment in which you are taking the survey, it must be as homogeneous as possible considering the purposes of your work; work objectives define the size of your survey'. We used to reply: 'But then, professor, the detection becomes subjective'. He replied: 'Precisely for this reason you must be very careful and well explain to everyone where you are taking the survey and why!'. He was right: without ecological homogeneity, ecosystems cannot be circumscribed and mapped. And it remains a subjective matter, indeed. We will see why here down, after describing what happened to the soil classification.

Soil classification has its own story. Already at the start, two very different classifications were born: simplifying, foresters considered the most organic surface part of the soil, calling it 'humus form', P.E. Müller in (Jabiol et al., 2005); agronomists concentrated on the most mineral part of the soil (which also contained the organic part buried with the processing) which they called 'soil'. While foresters selected morpho-functional traits, agronomists focused on climate (USDA) and physical–chemical composition, texture, structure and thickness of various diagnostic horizons (USDA and other National and International classifications), with the scope to provide mineral elements and nutriments for crops. Foresters tried to link humus forms to the floristic composition or soil animal lists (Hartmann, 1965; Hartmann & Marcuzzi, 1970; Klinka et al., 1981) and the ability to regenerate the forest (Bernier, 2018; Bernier & Ponge, 1994; Camaret et al., 2000; Ponge, 2009; Toutain, 1981). Agronomists, on the other hand, linked soil types to the specific climate and needs of crops (Beaudette et al., 2013; Berdugo et al., 2020; Birkeland, 1999; Brenna & Tab aglio, 2013; Jenny, 1941). Each country built its own classifications.

5.3 | Classical soil classification

For the soil, the need for unification was necessary when international organizations wanted to map soils at planet level. An exciting summary of the history of soil classification can be found in the FAO-website portal. The FAO-Unesco Soil Map of the World (1971–1981) is structured in 10 Volumes composed of a common Legend (Volume 1) and nine sections corresponding to different areas of our planet (Figure 3).

The first volume corresponds to a legend necessary to understand all the maps. We copied pasted in Appendix S2 some pages of this legend. They well illustrate the difficulties that have been overcome by the authors of this monumental work.

The authors of the cartography tried to respect the principles mentioned above (5.1. Crucial historical legacies). In FAO-UNESCO (1974), we can read: 'The number of soil units which compose the legend of the Soil Map of the World is 106. The legend sheets present these soil units in an order which reflects the general processes of soil formation. The basic principles which underlie the separation of these soil units and their definitions are discussed in Chapter 3. Areas of "non soil" are shown on the map as miscellaneous land units'. It sounded very promising. Unfortunately, the agreement was only apparent. It hid strong differences of thought that later revealed themselves in the construction of different national operational classification systems. The USA builts their own classification (Soil Survey Staff, 1975, 1999, 2003, 2010, 2014, 2015; Soil Science Division Staff, 2017), FAO and IUSS another (Charzyński et al., 2017; IUSS Working Group WRB, 2007, 2010, 2015; Jahn et al., 2006; WRB, 2006), and many states operated independently in their countries, often agronomists on one side and foresters on the other, example in http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/

VolumeI Legend
VolumeII NorthAmerica
VolumeIII Mexico and Central America
VolumeIV SouthAmerica
VolumeV Europe
VolumeVI Africa
VolumeVI SouthAsia
VolutneVI North and Central Asia
VolumeIX Southeast Asia
VolumeX Australasia

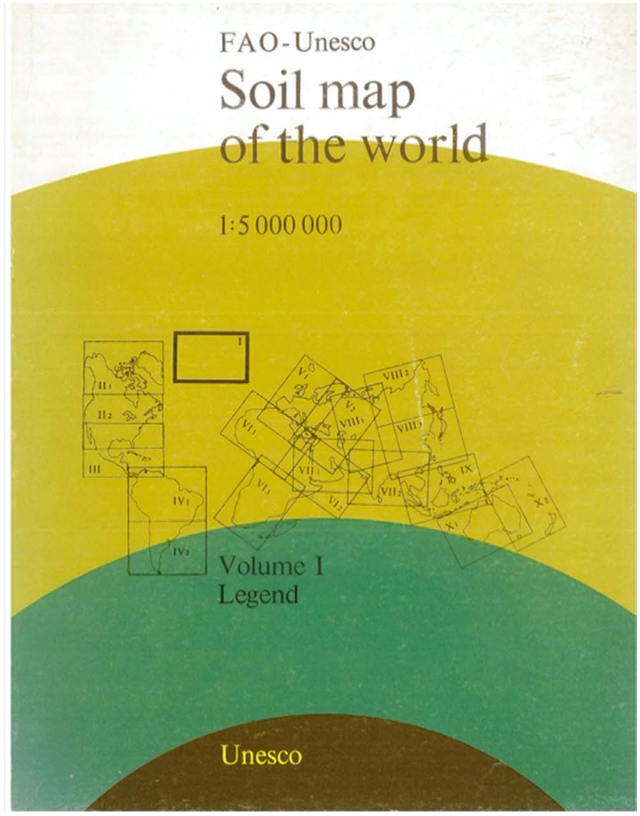

FIGURE 3 The FAO-Unesco Soil Map of the World, a first immense effort to synthetize the distribution of the soil on our planet. On the right the cover of Volume I, which is identical in the other volumes, only changes the squared that frame the described section. Notice the design, which recalls the horizons of the soil, but also soil, vegetation and atmosphere, or an interlocking of concentric circles typical of a modern ecological vision. Just beautiful, with the maps scattered as if in a vacuum

France (Afes, 2009). In Italy, for example, for historical reasons, the classification of soils depends on the regions in which it is practised: in the North West, the French one prevails, even for humus forms, in the North East, the German or USDA ones are adopted but the Austrian one for humus forms, and in the Central-South often the USDA is preferred, sometimes that of IUSS Working Group, while for humus, it is not uncommon to refer to a Canadian manual.

Even worse, when there are over three variables interacting, and in the soil, there are dozens, a natural system end up in a chaotic and unpredictable movement (Lorenz, 1963; Mayr, 1942). Soil profiles, as other natural systems, are all different and impossible to classify through a list of characters subdivided in categories. Jenny had foreseen it too (Jenny, 1941) – resumed in 5.1. Crucial historical legacies. It is thus impossible to give a name to the soil fixing the position of a diagnostic horizon in the profile, or the colour of this horizon using a panel of reference colours (Munsell), or the content of clay of this horizon. Each variable depends of so many other variables that in a given point in the field the combination of them is very large and unpredictable. However, soil scientists decided to separately improve existing classifications. The result was that the national classifications diverged over time, making it impossible to merge them into a single reference.

For some years now, the specialists of the different classification schools have been organizing joint outings, such as soil classification IUSS activities. The best attempt to make the classification easier to understand to other natural science specialists is that of the Soil Survey Staff (Staff Soil Survey, 2015), which proposed a beautiful Illustrated Guide to Soil Taxonomy (version 2) obviously based on the American system. The corresponding model of the World Reference Base Working Group was published in 2018 under the title of Essentials of Soil Science – Soil formation, functions, use and classification (Blum et al., 2018). What is most surprising in these manuals is the almost absence of information on soil biology (zero pages in the American Guide, 4 pages in the WRB Essentials), even if the 'fathers' of soil science put it in the second position, after the climate. And we know how much the climate itself is connected to the living beings of our planet, which have modified it to make it suitable for their development (Lenton et al., 2016).

5.4 | Is there a way to classify soil that is useful and also accessible to non-specialists?

To classify the soil in a simple way, it is necessary to define from the beginning the purpose of the classification and the 'limits of the boxes' in which it is useful to put the soils. The Unified Soil Classification System (USCS), for example, is a standardized method used in engineering and geology to describe the texture and grain size of a soil. It can be applied to most unconsolidated materials and is represented by a two-letter symbol. A similar 'logical' model is already used for agricultural soils, automated. The owner of a crop sends the soil sample to the laboratory that does the analysis and classifies that soil for that specific crop, and reports how much nutrients are missing to optimize its production. Although you may disagree on the principle that knowing what plants are made of (Fusaro, 2015; Lowenfels, 2017) makes possible to calculate what needs to be put into the soil, with arrangements over time and crop changes, the method works. There is now an important amount of work on the biological quality of the soil. Some among thousands of articles, historical context (Magdoff & Weil, 2004; Wander et al., 2019); European references (Balbo et al., 2006; Chaussod, 1996; Parisi, 1974, 2001; Ponge et al., 2013); climate change implications (Bispo et al., 2018; Brussaard et al., 2007; Yin et al., 2020).

In few words, a QBS index (Biological Quality of the Soil) is calculated by sampling soil animals, especially arthropods and worms. These animals are sorted into functional groups and the quality of these groups is studied in different types of soils. It can be seen if one soil is richer in functional biodiversity (which guarantees the functioning of the soil, with the right proportion between mites and springtails, for example) than another (Angelini et al., 2002; Nuria et al., 2011; Ruiz-Camacho, 2011). Similarly, soil microorganisms are classified into functional groups and designed to improve soil management (Nesme et al., 2016; Torsvik & Øvreås, 2002). Some of the countless scientific articles (Banerjee et al., 2018; Fierer et al., 2007; Finn et al., 2017; Pennanen et al., 2019; Uroz et al., 2016). There are even references for the public, with practices of use of microorganisms, including symbionts: (Lowenfels, 2014, 2017; Lowenfels & Lewis, 2010). There are also manuals for the classification of soil health, through the analysis of its physical, chemical and biological components, one example among many (Gugino et al., 2009). Some constructive criticisms among a countless number of works (Bellon-Maurel et al., 2010; Bünemann et al., 2018; Cano et al., 2018; Datta et al., 2016; Fine et al., 2017; Magdoff & Weil, 2004; Roper et al., 2017).

There are many useful ways to classify the soil, then, but none of them seems to satisfy what the founders of the soil science whished. They wanted to understand the soil on a planetary level, to appreciate how this system was distributed/developed on the planet in harmony with the planet life. Is there a way to achieve this?

5.5 | Soil and humus

When an artificial crop system is compared to a forest, things change. We should think to nourishing elements cycle for a whole system composed of species that have historically come together to collaborate and optimize energy resources. Forest managers call the attempt to mathematically imitate a natural forest-becoming as 'normalization' (Hasan et al., 2017; Mahdavi et al., 2019; Oldeman, 2012; Pan et al., 2011; Phillips et al., 2004; Reinmann & Hutyra, 2017; Susmel, 1980). The cycle concerns a part of the forest surface, a mosaic piece that regenerates when an old tree dies. It has been described and leads to the stability of the forest mosaic as a whole. The number of trees on the surface under renewal must decrease exponentially following a known curve with parameters related to the species and called 'norm'. Soil plays a fundamental role in the cycle, and it is rather the Humipedon (Zanella, Geisen, Ponge, et al., 2018) that changes over time, the whole profile following within a much longer time (Achat et al., 2015; Baldrian, 2017; Bernier & Ponge, 1994; Osman, 2013; Poeplau et al., 2020; Takahashi et al., 2019; Zanella et al., 2018).

The need to have one for all and international humus forms classification is quite recent. Unification began in July 2003, with a meeting in Trento (Italy) of 26 European specialists with the specific aim of arriving at a European proposal for the classification of humus forms. The need for unification arose from the necessity to accurately calculate the carbon cycle at the level of several European countries. The profile of a natural soil is very complex, and it is not enough to take samples at predefined depths to know the amount of carbon that it stores. It was better to subdivide the soil into horizons and then take a sample in each of them. The 2/3 of the carbon being concentrated in the organic and organo-mineral horizons, which correspond to the humus forms, it was decided to try to classify them in a standardized way. In 2018, the summary of the works (Figure 4) was published in 19 articles that make up 2 special issues of the Applied Soil Ecology Journal, volumes 122a and 122b (Zanella & Ascher-Jenull, 2018a). It was accompanied by another 58 in-depth articles in a third special issue, volume 123 (Zanella & Ascher-Jenull, 2018c).

If the soil acts as a living being, it develops and changes with the system that contains it, and depending on the

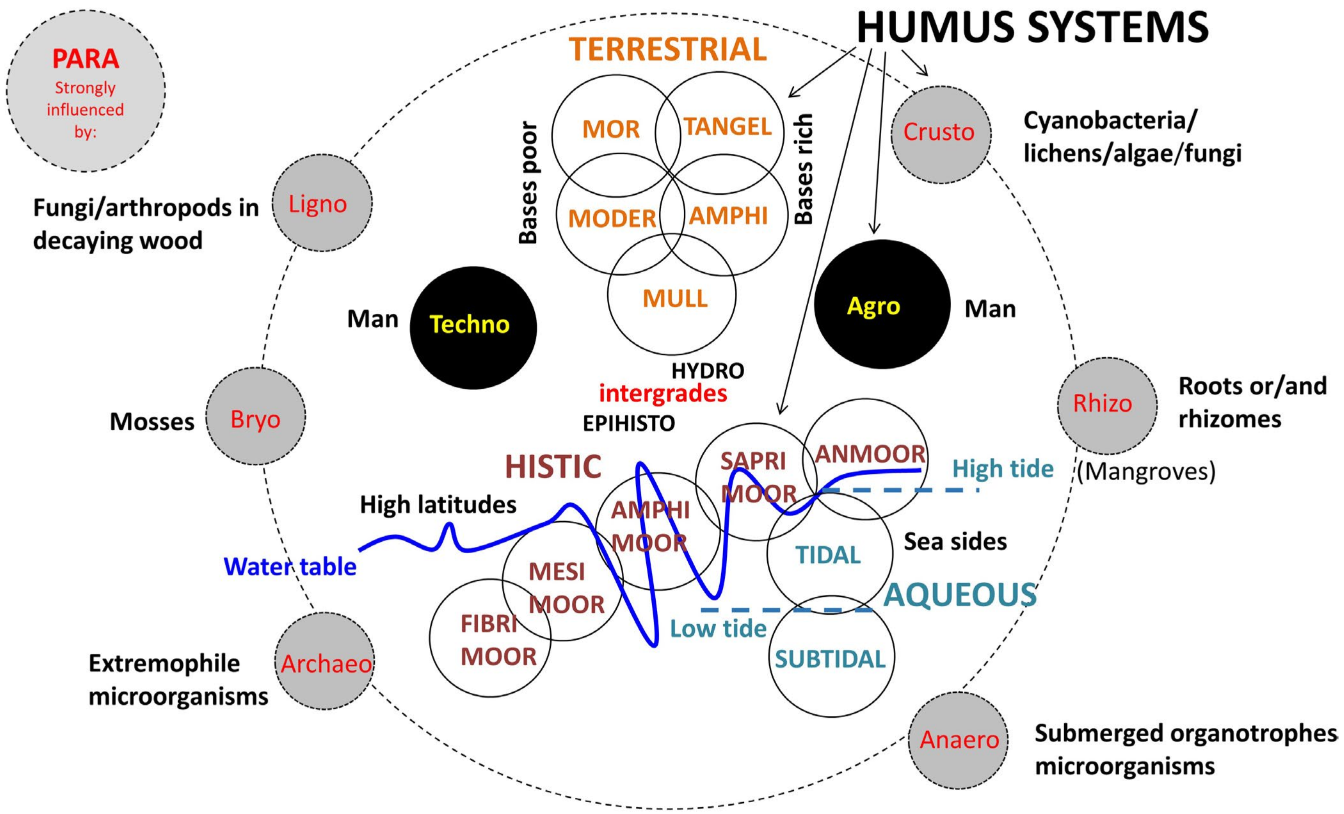

FIGURE 4 The 20 humus systems of the classification published by the Humus Group are divided into: 6 young or very particular natural systems (Para); 2 systems closely linked to man, one semi-natural (Agro) and one completely built by man (Techno); 5 terrestrial systems containing 17 humus forms; 5 Histic systems containing 16 humus forms; 2 Aqueous systems containing 3 humus forms. In total, the forms of humus described are 36 (not reported in the figure)

space-time scale with which one looks at it, it changes its appearance (Zanella et al., 2018). It seems like a trivial matter; in reality, it changes the perspective with which one has to look at the soil wanting to classify it. One way to classify soil taking into account its dynamics is to break it down into three layers which are evolving influencing each other but which remain and can be classified independently (Figure 5).

Living organisms organize the superficial part of the Earth's crust into layers that are visible to the naked eye (a necessary condition for the soil to be classified in the field with the naked eye; in general, a magnification of 10 times is also recommended). If we consider the soil as a living system, it begins with the colonization process of the rock by microorganisms (Time 1 on Figure 6). In time 2, we can see an organic matter that begins to bond with the mineral one and form aggregates (OA horizon), and the rock fragments generating an initial Lithopedon (C). In time 3, the organo-mineral aggregates become well amalgamated and form a structured A horizon. In time 4, a new layer called Copedon begins to form between well-developed Humipedon and Lithopedon; it arises from the interaction of them. In time 5, Copedon (horizon B) increases in volume and takes on a mature form. In time 6, we arrive at a complete, mature soil profile, where the Copedon can also present an E horizon.

Each soil horizon gets its own relative independence: since it is built by living beings and develops by its own, it can also be considered a subsystem contained in a larger complete soil system. As the complexity of the body of a living organism may be reduced in its different organs, it is thus possible to break down the soil profile into horizons contained in three ‘organ-like’ parts: Humipedon (organic horizons OL, OF and OH and organic mineral A); Copedon (mineral horizons E and/or B); Lithopedon (mineral horizons C and R). The advantage is that of being able to study these parts of the soil as if they were independent, this is done with organs, when you want to understand how an organism works. In the natural environments, the formation of the soil profile can stop at Humipedon (soil Crust, layer of microorganisms on bare rock) stage, or also get a Lithopedon (high altitude, soils such as Rendzina or Rakers, for example), or form an additional Copedon (the most common adult soils) which may be even very large in comparison to Lithopedon and Humipedon (in tropical soils in general); soil can also lose its Humipedon later on (eroded soils), or possess only a Lithopedon (moon soils, for example, that lack of life).

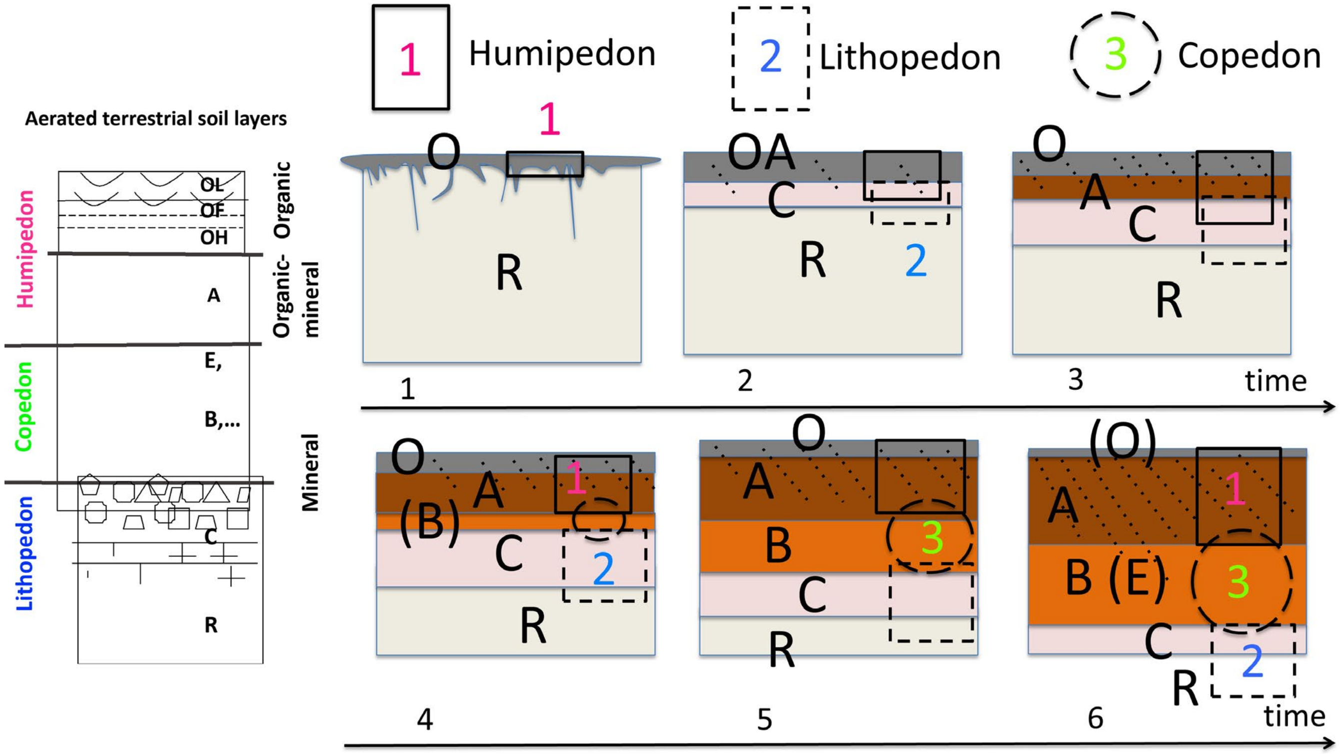

FIGURE 5 On the left, the 'layers' that can be identified in the soil profile. On the right, the phases of formation of the soil profile

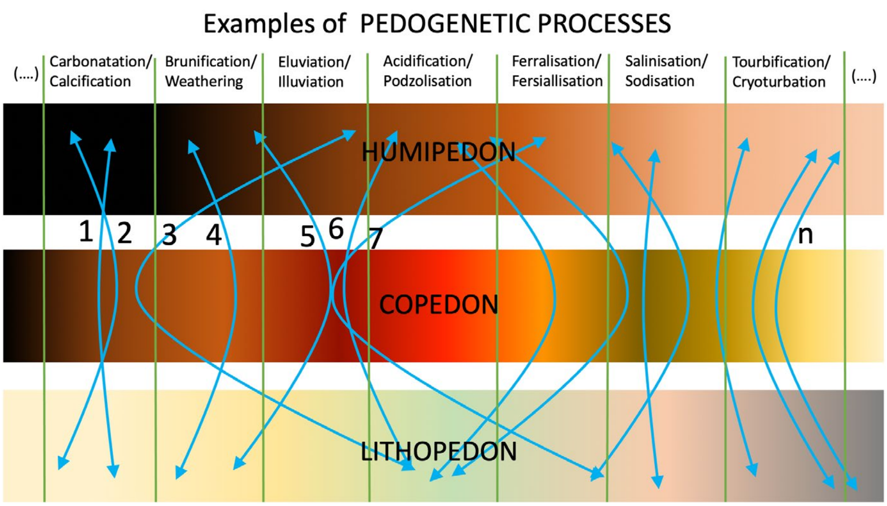

FIGURE 6 Soil is more complex than we think. It is almost as if it was an underground forest, much more concentrated and with less air than that which lives above the ground. We can imagine it composed of three layers in which it evolves without being perceptible in its dynamic state. Perhaps the blue arrows can represent the large groups of soils described by the modern IUSS Working Group, and give an idea of this concept[3]

Moving on to classification, morpho-functional boxes were chosen for the humus forms. For example: humus forms of a Mull system are all those in which the litter disappears within one year. Which translated into a morpho-functional field parameter becomes: to create an OH horizon (last stage of litter transformation by soil organisms, a layer of organic dust/thin fragments, mixed with small animal droppings) takes at least one-year time. Thus, it was decided that when there is no OH horizon, the humus form should belong to a Mull system. Once a

[3][Correction added on 21 November 2021, after first online publication: This is an updated version of Figure 6.]

precise definition of the OH horizon made, the classification of the Mull system was available and easy to use in the field. A similar reasoning was made for the other humus systems: Moder = with OH, and with gradual transition towards an A horizon on acidic parent material; Amphi = with OH, and with gradual transition to an A horizon on non-acidic parent material; Mor = with nozOF and / or with clear transition between organic and mineral horizons; Tangel = with an A horizon that shows less than half the thickness of OH. In each system, the different humus forms are only a matter of measurable thicknesses of the diagnostic horizons. A free available iOS or Android app may help to remember the diagnostic characters and to classify the topsoil. The same reasoning was done for Histic (submerges topsoils), Aqueous (tidalic seaside topsoils) and Para (initial, very young and pioneer, or man-modified and artificial topsoils) systems. The underlying principle is very similar to that described in the FAO-UNICEF map legend: we have tried to circumscribe a surface volume of the earth's crust that grows over time and evolves as a system (called pedogenetic processes by soil scientists), dependent on those same soil-forming factors reported in the preceding Crucial historical legacies (section 5.1.).

To obtain a classification of the soil also on a biological basis, it would be enough to do the same proceeding for the Copedon and Lithopedon that is to identify some a priori boxes, corresponding to the different processes of pedogenesis connected to them. In practice, it is only a question of cutting from the classical classification of the soil what could be Humipedons, assigning the remaining horizons to a process of formation and evolution, which despite being partly dependent on the one taking place in Humipedon, has its own relative autonomy and is easy to identify in the field (e.g. Eluviation, with the formation of an E horizon in missing the finished in Bt clay). In Figure 6, the subdivisions (which are rarely abrupt) within the three soil layers are expressed with colours. The arrows correspond to soil systems moving within these layers. It is the latter that together originate the soil but they have their own dynamics partly independent of the soil.

Reviewers asked for a table summarizing the thinking expressed in this part of the article. It is true that we do not even know what needs to be done to get out of the impasse. A biological classification of the soil on a DNA basis could probably clarify the living essence of the soil (Table 1).

The forms of humus are directly linked to particular groups of soil animals (Ponge, 2003, 2013; Zanella et al., 2012) and agents of biodegradation which are surely in turn linked to soil microorganisms (Bayat et al., 2018; Bispo et al., 2018; Karimi et al., 2018, 2019; Liang et al., 2019; Sofo et al., 2014,2019). This connection could have very important consequences on the management of forest and agricultural soils to stop climate from warming. The ultimate goal could be to integrate in the new classification all those data relating to biological functioning that are now collected by people who already practise a non-specialized soil classification (section 5.4).

From another point of view, which is the one concerning agricultural soils, that produce food not only for humans, it was thought that to transform/modify and work at will the soil was a scientific and profitable action. Originally, it was never thought that the soil was a system to be protected due to its historical biological structure and composition. Hans Jenny became aware of the possible misunderstanding and in 1980 published a book (Jenny, 1980) on the basis of a very modern definition of soil: 'Soil as an Object of Nature - Soil is more than farmer's dirt, or a pile of good topsoil, or engineering material; it is a body of nature that has its own internal organization and history of genesis'. In a letter to Science of the same year, he even wrote: 'Because of a possible climatic warm-up, we do not wish accelerate humus oxidation and the concomitant flux of carbon dioxide from soil into the atmosphere... The humus capital, which is substantial, deserves to be maintained because good soils are a national asset'.

6 | WHICH AGRICULTURAL PRACTICES CAN BE DEFINED SUSTAINABLE?

6.1 | Conventional or organic agriculture?

Nowadays, agricultural production is at risk due to many adverse abiotic and biotic factors. Furthermore, climate change can potentially decrease the effectiveness of plant defence mechanisms and increase the risk of diseases through excess growth and physiological alteration of cultivated plants (Vitti et al., 2016). In terms of increased temperature and extreme precipitation regimes, whether aridity or flooding, climate change will have detrimental agricultural consequences due to the interrelations between climate, land and water use, soil degradation and landscape changes (Dale, 1997; Tsiafouli et al., 2015). Nowadays, food security is an increasing concern in a growing number of countries. This situation calls for a relevant appraisal of factors that could affect crop production. One of the factors promoting a sustainable food production system is soil biodiversity (Sofo et al., 2020b). Unfortunately, despite the promotion of sustainable soil management by the Global Soil Partnership since 2012, in many cases soil management is still focused on directly

TABLE 1 Historical legacies

Historical legacies	
Dokuchaev (1900)	Climate, biological agents, rock, topography and duration are the factors of soil differentiation, or the factors of pedogenesis Climate and corresponding vegetation are the main ones responsible for the organization of soils on a global scale At the field scale, climatic variability does not have to be considered while topography and variability of the geological substrate can still modify soils There were exceptions to the climate zonality. Locally, this or that environmental factor plays a preponderant role and masks the role of climate. 'Zonal' soils, that are part of the climatic zonality; 'azonal' soils, whenever the rock outcrops directly; and 'intra-zonal' soils, whose characteristics are linked to special conditions, such as excess water or salt
Jenny (1941)	The soil system is an open system The initial state of the soil system has been designated as parent material. In selecting climate (cl), biological agents (o), rock (r), topography (p) and duration (t) as the independent variables of the soil system, we do not assert that these factors never enter functional relationships among themselves
Soil and vegetation	Soil and vegetation correspond to a continuous layer that shows changes inside and outside perceptible to the human eye Both soil and vegetation covers can be broken down into sub-layers Circumscribing spatial sub-units (horizontal or vertical soil and vegetation sub-units) is not so simple, because the transition from one to the other unit is rarely abrupt; very often it is gradual and nuanced We know that using the characteristic species of the phytosociological units to map the forest vegetation, the part of the forest occupied by undefined vegetation types becomes larger than that occupied by known vegetation types It is crucial to choose carefully the environment in which you are taking the survey, it must be as homogeneous as possible considering the purposes of your work; work objectives define the size of your survey
Need of unification	The need for unification is necessary when international organizations wanted to map soils at planet level The number of soil units which compose the legend of the Soil Map of the World is 106. The legend sheets present these soil units in an order which reflects the general processes of soil formation. The basic principles which underlie the separation of these soil units and their definitions are discussed in Chapter 3. Areas of 'non soil' are shown on the map as miscellaneous land units The disagreement among soil scientists produced a scientific impasse When there are over three variables interacting, and in the soil there are dozens, a natural system end up in a chaotic and unpredictable movement Illustrated Guide to Soil Taxonomy (2015). USDA attempt to approach a larger audience (ecologists, environmental scientists, etc.) Essentials of Soil Science—Soil formation, functions, use and classification (2018). WRB attempt to open to other disciplines
Soil as living system	Living organisms organize the superficial part of the Earth's crust into layers that are visible to the naked eye Each soil horizon gets its own relative independence: since it is built by living beings and develops by its own, it can also be considered a subsystem contained in a larger complete soil system To classify the soil means to circumscribe, a surface volume of the earth's crust that grows over time and evolves as a system (called pedogenetic processes by soil scientists), dependent on those same soil-forming factors Topsoils are directly linked to particular groups of soil animals. This connection could have very important consequences on the management of forest and agricultural soils to stop climate from warming
Jenny (1980)	Because of a possible climatic warm-up, we do not wish accelerate humus oxidation and the concomitant flux of carbon dioxide from soil into the atmosphere... The humus capital, which is substantial, deserves to be maintained because good soils are a national asset
Solution?	A biological classification of the soil on a DNA basis could probably clarify the living essence of the soil

managing soil fertility, rather than on protecting soil biodiversity as a whole or single species individually, although soil biodiversity is known to be a main agent of soil fertility (Altieri et al., 2015).

The application of pesticides, herbicides and mineral fertilizers, typical of conventional agriculture, cannot be considered an eco-friendly approach for crop production and defence, as their massive use can provoke water contamination, air and water pollution, and release of harmful residues and by-products into the soils (Blouin, 2018; Korkina & Vorobeichik, 2018; Van Groenigen et al., 2019). A decrease in soil quality due to conventional soil management negatively influences important ecosystem processes, like nutrient cycling and carbon sequestration (Bampa et al., 2019; Blouin et al., 2005). On the other side, sustainable, conservation and/or regeneration agriculture offer new chances to mitigate the effects of climate change. In sustainable agroforestry systems, management practices are able to increase carbon (C) inputs into the soil and possibly reduce greenhouse gases (GHGs) emissions due to some revised field operations, for example, by irrigation, use of recycled water, pest and disease management, fertilization, and soil and plant farming systems (Mutuo et al., 2005). In turn, carbon enrichment increases biological activity by improving soil structure, as well as soil moisture and nutrient content that are beneficial to plant growth and production (Marinari et al., 2000). As Lago et al. (2020) recently indicated, there is clear evidence that more environmentally friendly land management represents a promising strategy to increase soil C sequestration.

6.2 | Soil and vegetation co-evolve

Soil functions as a living system. Climate, organisms, topography, parent material and time completely describe the soil system. Soil and vegetation co-evolve implementing other living beings and creating the well-known zonation of biomes of planet Earth. In recent years, soil quality has been recognized to play a double role in the entire agroecosystem: it is important for a good production as well as for a healthy environment (Doran & Zeiss, 2000). In conventional agriculture, still adopted by most farmers, frequent soil tillage strongly reduces the complexity and diversity of soil microbiota (Adl et al., 2006). For this reason, conventional, non-sustainable agronomic practices should evolve in a more sustainable management addressed to ameliorate the ecological networks and nutrient cycles, in which soil microorganisms are involved. The adoption of sustainable soil management practices and organic agriculture can be eco-friendly and safe methods to ameliorate plant physiological status, reduce plant disease incidence, and increase yield and quality without side damages to the environment and human health. For instance, it would be possible to adopt a sustainable approach that enriches the soil with biocontrol microorganisms with action against pests (El-Tarabily & Sivasithamparam, 2006), plant-growth-promoting microorganisms able to promote plant growth and development (Abhilash et al., 2016), and microorganisms able to increase the availability and uptake of essential nutrients in plants, for example mycorrhiza for P (Bolan, 1991) and nitrogen-fixing bacteria for N (Shu et al., 2012).

In this scenario, the advantages of the adoption of a sustainable management (or conservation and regeneration agriculture) that includes no/minimum tillage, cover crop application, incorporation of grass and crop residues into the soil, and endogenous and exogenous soil carbon inputs (Palm et al., 2014) can be a key factor to enhance soil quality/fertility and production in a sustainable way, preserving natural resources and avoiding detrimental effects on the environment. Such benefits include a high level of soil microbial genetic/functional diversity and complexity both in the soil (bulk soil and rhizosphere) and in the plant (phyllosphere, carposphere and endosphere) (Figure 7), a faster C and N turnover, higher levels of SOM and soil water content, and better soil physical and chemical characteristics (Fausto et al., 2018). Inappropriate or exploitative crop agroecosystems represent a key threat for soil degradation through erosion, nutrient depletion or structural collapse (FAO, 2015, 2018). Increasing our knowledge on biochemical processes of soil microorganisms and animals involved in C and N dynamics that influence in turn their availability for plants (Didden et al., 1994; Shaffer et al., 2001) will lead to optimize management strategies for a multifunctional concept of agriculture.

Addressing knowledge gaps of sustainable practices is of fundamental importance as an entry point to improve growing techniques and for understanding wider soil processes, such as consequences of land use or climatic change on both biodiversity and soil ecosystem services. The research should be focused on developing an ecological and holistic approach that combines traditional soil health assessment with sensitive indicators of the effects of the soil environment on soil microbial and faunal communities and cultivated plants, such as community dynamics (taxonomic, genetic, functional and metabolic) and plant stress physiology, mostly assessed by growth/yield, hormone levels and photosynthetic capacity (e.g., photosystem II activity). The sustainable approach will lead to a better understanding of the effects of management practices on soil organisms and plants. In the long-term, soil health should be included as a factor when management decisions are made by farmers, land managers and crop advisers. The

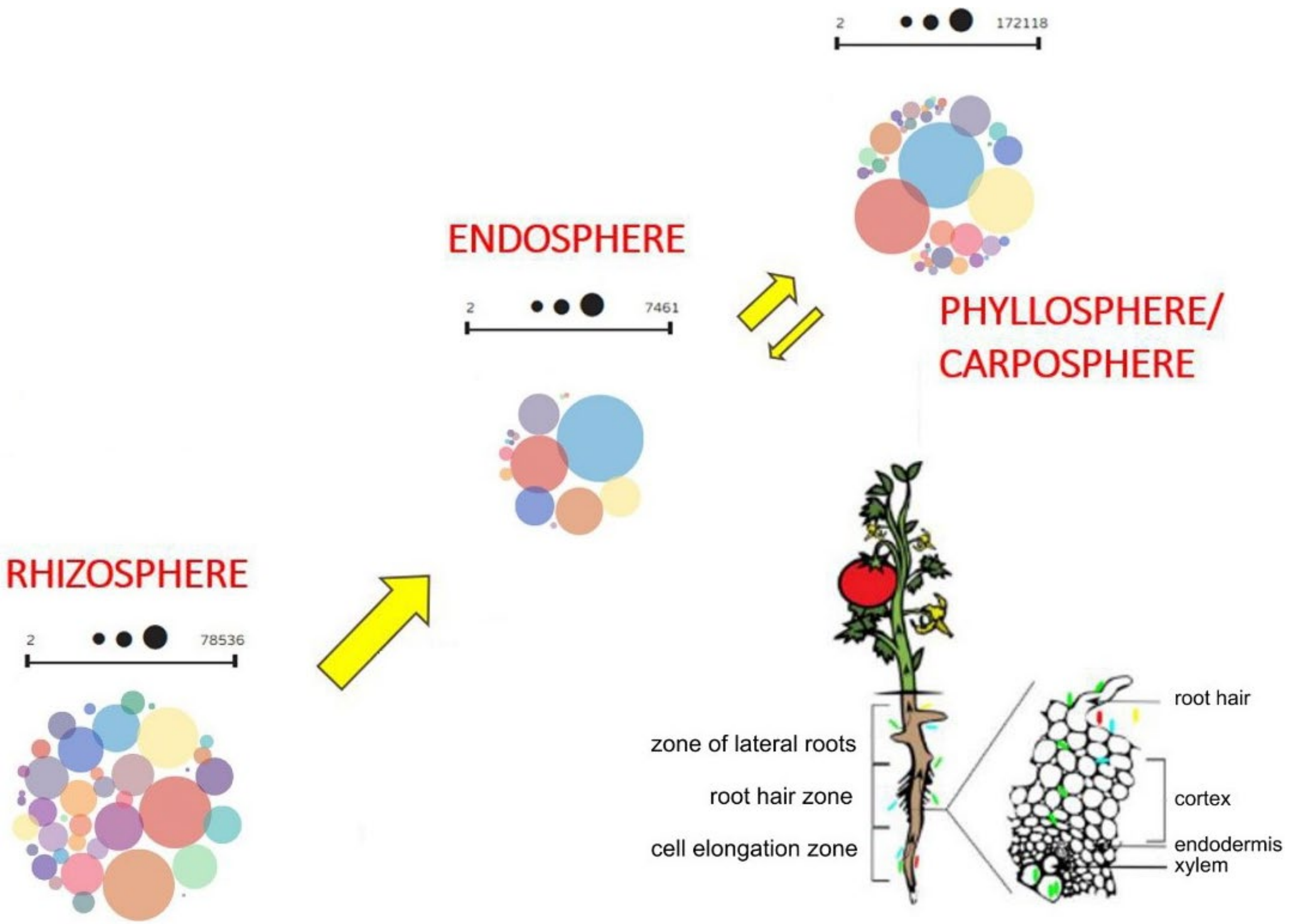

FIGURE 7 Bubble charts of the values of bacterial relative abundance in rhizosphere, endosphere, phyllosphere and carposphere (leaf and fruit surface, respectively) at class level of olive plants. Each bubble represents a bacterial taxon filled with a specific colour, the size of which is proportional to the summary level of this taxon in the examined samples. The increasing scale of the total reads, represented by the smaller bubbles to the bigger ones, is displayed above each bubble chart. The arrows indicate the degree of bacterial transfer among the different compartments. Endosphere is the poorest in terms of microbial abundance and diversity, because of the highly selective environment. Kindly contribution by Alba Mininni

studies should not be designed for a systematic monitoring of the differential effects of each component of sustainable practices such as soil cover, manuring, reduced pesticide use or reduced tillage (Hobbs et al., 2008), but with these practices in combination, in order to have an overall vision of the agrosystem, and how to manage it sustainably (Figure 8). In this view, the metagenomics (that is the microbial identities and functional gene information) and the metaphenomics (that is the product of the combined genetic potential of the microbiome and resources) of bacteria or fungi (Fierer, 2017; Jansson & Hofmockel, 2018) would allow to define the microbial communities living in the different soil layers. The DNA/RNA-based identification of specific alive and active bacterial/fungal taxa, according to their functional distinction (aerobic/anaerobic, saprophytic/parasitic/pathogenic, autotrophic/heterotrophic), can be of key importance for defining the microbiological fertility of a soil and its response to agricultural practices (Badagliacca et al., 2020; Crecchio et al., 2004). Identification by DNA fingerprinting, originally developed for the identification of poorly culturable microbial strains, has become a rapid and cost-effective method of current use in agricultural soils (Sofo et al., 2019a). It has been extended to the current assessment of nematode communities (Wang et al., 2008) and its application to other soil fauna is promising, although still not in current use (Orgiazzi et al., 2015). Finally, eventual pathogenic organisms and mycorrhization index should be monitored, identifying probable microbial pathogens and/or anaerobic microorganisms by a culture-based approach (*Phytophtora*, *Clostridium, Bacillus*, etc.) and presence and types of mycorrhiza, including DNA analysis of eventual pathogenic microorganisms during the growing season.

The application of endogenous and exogenous carbon inputs would be necessary for improving soil status. Using specific commercial products containing biostimulants

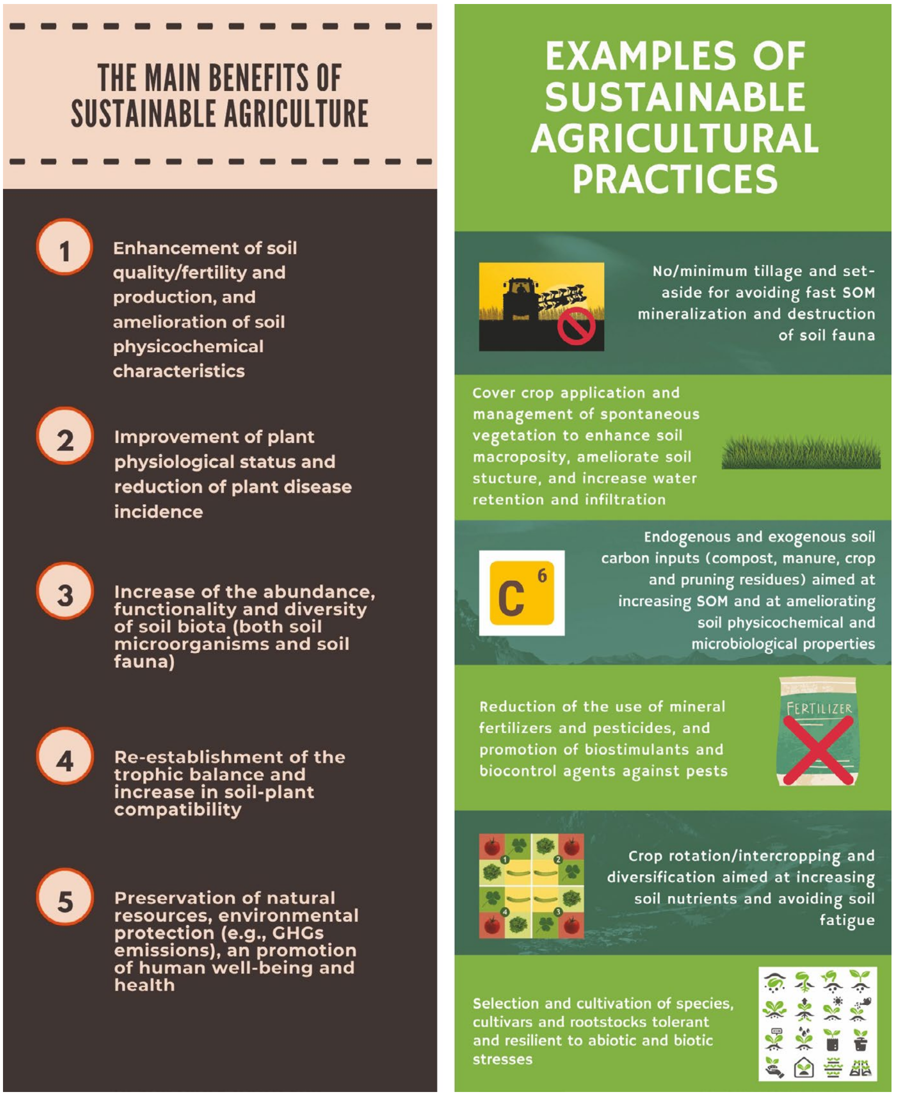

FIGURE 8 Major benefits of the adoption of sustainable agricultural practices. Examples of the sustainable agricultural practices explained in the text

and biocontrol agents to improve physicochemical and microbiological properties of the soils could increase resistance against eventual pathogens and enrich soil microbial communities. The application of compost, manure, soil management techniques for facilitating water horizontal movement in the soil, use of decompacting plants (e.g., *Raphanus* spp. or other Brassicaceae) would facilitate water vertical movement in the soil, both directly (Whelan et al., 2013) and through a favourable influence on earthworms (Pérès et al., 1998). On this basis, a sustainable management is a key factor for increasing the functionality and diversity of soil biota that enhance soil biological fertility. This amelioration leads to a higher soil quality, stability and multifunctionality, positively affecting plant physiological status and crop productivity.

Over the last decades, intensive agricultural practices (e.g., continuous soil tillage, high inputs of mineral fertilizers, application of low-quality irrigation water, removal of pruning residues) have determined the loss of soil fertility and the depletion of soil organic matter (SOM), with negative effects on both productivity and soil conservation (Bonanomi et al., 2011). Many conventional agronomic practices have a negative impact on SOM (Arrouays & Pelissier, 1994), the soil microbiome (Lupatini et al., 2017) and soil trophic networks (Tsiafouli et al., 2015), causing a decline in fertility: soil levelling (with consequent elimination of the organic horizon in many areas of the plant), deep tillage with a surface carryover of mineral horizons (non-organic), soil sterilization with destruction of microbiological diversity, the continuous and massive use of herbicides, mineral fertilizers and pesticides with biocidal action, and so on. Sustainable agronomic practices foresee a reworking of agronomic management which includes the reduction of the use of mineral fertilizers and pesticides (including cupric products), the rationalization of irrigation, the management – and not the elimination – of spontaneous vegetation and the contribution of different types of organic matter to restore the ecosystem complexity and heterogeneity, without leaving aside a careful analysis of the fields and the state of the plants, of the environmental conditions (pedological, microbiological, orographic and microclimatic), and, above all, of the agronomic and ecological history of the fields. The correct use of formulations of materials of natural origin, specially designed and processed according to the different cultivation and business conditions, can quickly re-establish the trophic balance and soil–plant compatibility, reactivating the nourishment of the crops and increasing their resistance to pathogens and parasites. Thus, soils rich in organic matter, or regularly fertilized organically with compost and vegetable residues (possibly not coming from the same crop), have a greater microbiological biodiversity. Crop rotation with phylogenetically distant species, the practice of fallow and crop associations make it possible to prevent or eliminate the decrease in soil fertility, and the use of graft carriers with tree crops can be helpful to mitigate problems of replanting of the same species. The crop succession, the inter-cropping of different species, the use of rootstocks phylogenetically distant from the cultivated variety make it possible to overcome the problems related to the decline in soil fertility. A very effective sustainable technique appears to be the use of compost tea, infused or more commonly fermented with compost, which has already been the subject of growing scientific and applicative interest for several years (Scheuerell & Mahaffee, 2002; St. Martin et al., 2020; Villecco et al., 2020). The technique is based on the use of different compost, specially selected (and sometimes, according to the needs of the plant, combined with non-composted organic substance), placed in infusion under aerobic conditions.

6.3 | Soil functions as a living system

Nowadays, there are evidences that sustainable management practices (e.g. no-tillage, supply of organic fertilizers, mulching of pruning residuals and cover crops, reduction or even suppression of pesticide use) can contribute to re-carbonize soils and reduce soil CO_2 emissions, recover soil fertility and increase yield. In sustainable agrosystems, because of the composition of the recycled biomass (pruning residuals, leaf fall, cover crops) and of newly supplied (e.g., compost, manure), a huge amount of nutrients is released if external supply of mineral fertilizers could successfully be replaced. However, considering processes determining N availability (organic matter mineralization, leaching, cover crops uptake, etc.), interactions among nutrients (e.g., antagonistic effects), variability of soil moisture and mineral nutrition, a particular attention is required. Sustainable agriculture can give benefits to plant growth, such as increased biomass and productivity, enhanced photosynthesis and carbohydrate allocation, better regulation of root respiration and higher defences against pests and diseases, with more soil microorganisms and fauna, and thus more efficient trophic networks. Mycorrhizal fungi, being involved in many ecosystem services (Stevenson, 1994), are important in many types of soil. Besides well-known negative effects of conventional practices (Verbruggen et al., 2010), in over-exploited, conventionally managed agricultural landscapes, habitat loss and fragmentation prevent dispersal and are major threats to mycorrhizas (Longo et al., 2016).

Human societies benefit from a multitude of ecosystem services from both natural and managed ecosystems, to which soil organisms make a crucial and distinctive (Stevenson, 1994). Unfortunately, it is well recognized that humans are changing the global environment at an unprecedented rate. An increasing proportion of the world's population is urban or suburban. For this reason, the demand to extend cultivated areas in cities is increasing, prompting to establish, restore and sustain urban ecosystems. In urban ecosystems, the selection of cultivated or ornamental plant species to use on roofs and walls, has often been based primarily on their ability to cope with the harsh conditions of the urban rooftop environment (e.g., high wind and irradiance, lack of organic material and nutrients, intermittent drought) (Figure 9). In these new anthropogenic environments, the application of organic inputs and bio-products, included in sustainable agricultural practices, can be crucial for plants' survival. Sustainable agriculture can cause recreational, human health, economic and environmental benefits. The latter also includes lower GHGs emissions because of reduced use of synthetic fertilizers and pesticides, lower leaching losses to groundwater (e.g., nitrates and nitrites), and no eutrophication of ponds and streams because of excess phosphorus and nitrogen. Comparisons of soil biota across wild, rural and urban habitats have revealed dramatic differences between sustainably managed and conventionally managed areas, with the lowest biodiversity in the latter (Antonelli et al., 2020).

Regardless of practical challenges, there is untapped potential for sustainable agricultural practices to influence environmental outcomes, citizens' consciousness and market's trends soon (Scotti et al., 2015; Stevenson, 1994). The results of many recent studies encourage the use of sustainable agricultural practices able to enhance soil fertility (Diacono & Montemurro, 2010; Kassie et al., 2013; Scotti et al., 2015). The ultimate goal is to convince farmers to adopt a sustainable farming system as a whole, and not just as individual elements/practices, in order to promote good-quality production without negative effects on the environment. For achieving this, the approaches should not be 'top down', but they must be 'bottom up', where

FIGURE 9 Urban green roofs. (Top row) from left to right: green roofs in old buildings (Milan, Italy); vertical forest skyscraper (Milan, Italy); garden terraces (San Francisco, USA). (Central row) from left to right: 'food roof' with vegetables (Trani, Italy); Mohri Garden at Roppongi Hills (Tokio, Japan); green roof of Kyoto railway station (Japan). Pictures by Adriano Sofo

farmers and citizens help to co-design and co-deliver soil management and food production systems (Ajayi, 2007; Kassie et al., 2013). It is time to switch to a modern and multifunctional concept of agriculture based not only on the production but above all on product quality, environmental protection, resource saving and promotion of human health.

6.4 | Soil is organized into layers

The complexity is such that the time distinguishes at least three groups of layers in the soil: Humipedon, Copedon and Lithopedon. Microorganisms and plants condition the Humipedon evolution by generating a known series of systems that starts on mineral substrate and divides in two series, in submerged environment (Archeo, Anaero, Histo and Aqueous systems) and out of water in aerated sites (Crusto, Bryo, Rhizo, main Terrestrial systems) (Zanella, Ponge, & Briones, 2018). Animals interact with microorganisms and plants in each system. Each system is structured around particular organisms and which have co-evolved for millions of years.

Microorganisms and plants condition the Humipedon. Mineralogical aspects and more related to soil physics are more decisive in Copedon. The geological history of the soil and the cycles of some minerals are much more important in Lithopedon. The time separates the studies of these three soil layers, handing them over to specialists who meet periodically to make the right synthesis. The soil is a single body that reacts as if it was composed of superimposed organs. Soil classification must take this crucial aspect into account. Humipedon reacts over the years and up to a few decades; Copedon takes from decades to hundreds of years; the Lithopedon centuries to millennia.

We must no longer think we can move, manipulate, destroy, create soil as if it were an inanimate object. Soil has its own internal, historical and precious organization: what we need to do is discover it and use it well. It is necessary to understand these processes well before intervening with means that risk destroying the 'superimposed organs' of the soil.

Agrosystems (crop soils) correspond to artificially simplified natural systems (in general Mull Humipedons). When artificialization is extreme, we talk about Techno systems (hydroponic or compost are examples of that). These phrases hide an underestimated truth of intrinsic value. Agrosystems are not alternative systems, but old systems are reorganized by man. The soil system incessantly tries to return to its original organization, made of different overlapping layers, but the work of using its stored energy takes it back annually in time. At the end of a conventional exploitation process, there is a soil poor in organic matter and life, an original mother rock of the soil. We must no longer think we can move, manipulate, destroy, create soil as if it were an object and then expect it to work as a living system to render service to us. It is like catching a lion in an African savannah, taking it to the Alps and feeding it roe deer. This would not work. Or rather, it would work, like in a zoo, but spending energy to create and keep alive another unbalanced system; it would be better to preserve original systems and try to co-evolve with them.

If the purpose of conventional agriculture is to build new soils, then we need to think about building Copedons between Humipedons and Lithopedons, not destroying this historical organization. Ask us what these layers really are (studying natural references) and how they can be built in compliance with natural and biological laws. It is perhaps possible to build new Humipedons. This is what we try to do with composts or hydroponic solutions. We can try to make them better, more like existing Humipedons. The other possibility is organic farming. The right method should be very similar to the one proposed by Masanobu Fukuoka in his famous book 'Natural Way of Farming' (1985): to intervene as little as possible. Understand how it works and accompany the movement, changing the cards in the game as little as possible. It is difficult and, for this reason, it is the right way, and it needs a scientific preparation of high naturalistic/biological level.

6.5 | Agroforestry

This is also an important point, not detached from the previous one. The agroforestry use of the lands of our planet is often presented as an ecological and sustainable method of exploitation both internationally and nationally. The concept is acceptable. It is known how trees increase the volume of the ecosystem, with helpful implications in the air and soil parts of the ecosystem (Altieri et al., 2015; Jose, 2009; Marsden et al., 2019; Wang et al., 2020).

What must be avoided is that it becomes a disguised method of stealing more land from the forest. Since the part already taken (1/2) does no longer satisfy a humanity in search of food, we operate on the part that remains transforming it into an agricultural forest. If the process is conceivable for the ecological exploitation of those parts of the forest (equatorial and otherwise) which have already been converted into cultivated fields and then abandoned, it should be banned in the still forests, whether they are treated with tall trees or coppices.

7 | CONCLUSIONS AND FUTURE INSIGHTS

In this paper, we presented cross-disciplinary and holistic approaches applied to agricultural soils. From the analysis of the literature, it emerges that in an agrosystem, from an ecological point of view, understanding the relationship between local changes (e.g., soil microorganisms/fauna) and global effects (e.g., soil quality/fertility, soil environmental importance, global change) – the so-called 'local to global' concept – aims relevant and innovative. Converting the conventional management systems of agricultural land into more sustainable and environment-preserving systems has become urgent. Conventional vegetables and fruit production, because of the unavoidable lack of resources (particularly soil and water), is going to be economically and environmentally disadvantageous, while, on the other side, organic farming, whose benefits and costs are controversial, is not always self-sustaining and durable, and it cannot cover the enormous and increasing world demand. For avoiding this dilemma, the productive systems should be directed towards the principles of an innovative, sustainable, regeneration and conservative agriculture, which includes rationally the existing and innovative agro-technological practices, such as no- or minimum soil tillage, on-site nutrient input and recycling, adequate irrigation and rational management of crop residues. This innovative approach, aimed to keep production at a high level and cultivating lastingly, can render a wide range of benefits to farmers and the environment. In addition, better understanding the role of soil fauna in such systems has a key role to adapt management strategies and mitigating GHGs emissions. Furthermore, the role of soil organisms (both microbes and animals) to ecosystem services and their close relationship with soil organic matter has been often overlooked, while it should be seriously taken into account in future land management strategies.

The world's soils are rapidly deteriorating because of soil erosion, nutrient depletion and other threats, but sustainable practices and technologies can reverse this trend. One key point from the new IPCC report (IPCC, 2019) is that conventionally tilled soils erode over 100 times faster than they form and that land degradation represents 'one of the biggest and most urgent challenges' that humanity faces. Humans have degraded roughly one-third of the world's topsoil, and about 3.2 billion people – more than a third of humanity – already suffer from the effects of degraded land. Continuing down this path does not bode well for feeding a growing world population. Barriers to adopting regenerative farming systems include force of habit, lack of knowledge about new practices and real and perceived economic risk during the transition. The benefits of rebuilding healthy, fertile soil are clear. Economic benefits of land restoration average 10 times the costs (IPCC, 2019). Thus, sustainable agriculture appears to have a big economic, social and political impact (Baggaley et al., 2020). We trust that sustainable agriculture will contribute to understand how important the soil as a living matrix is for both climate regulation and plant production. A better grasp of how soil organisms interact with organic matter turnover and stabilization will open novel ways for the sustainable management of soils. It is time to take soil seriously in consideration and to rethink humanity's relationship to the environment and particularly to soil. In their article, Kopnina et al. (2018) hope for change from an anthropocentric mentality based on human-centred values and things to a more comprehensive vision that includes non-human living beings and things, such as environmental life-support systems. Thus, it would be necessary to promote a general law of soil protection, as soil produces food and sustains all ecosystems, independently from human need to economically grow. People need to change agriculture and land use, and we all wish to have 'more sustainable' soils, the only basis for a healthier world.

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