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Opinion

Depletion and Recovery of Soil Organic Matter: Ecological, Economic and Social Implications

Mattia Napoletano [1], Alessandro Bellino [1,*] and Daniela Baldantoni [1,2,*]

[1] Department of Chemistry and Biology "Adolfo Zambelli", University of Salerno, 84084 Fisciano, Italy; mnapoletano@unisa.it (M.N.)

[2] National Biodiversity Future Center (NBFC), 90133 Palermo, Italy

[*] Corresponding authors. E-mail: abellino@unisa.it (A.B.); dbaldantoni@unisa.it (D.B.)

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ABSTRACT: Over the past decades, urbanization, industrialization and unsustainable management have impaired soil fertility and ecosystem functioning, thereby affecting ecological stability and economic development. The mechanistic coupling between pressures and effects lies in the loss of soil organic matter (SOM), which directly and indirectly controls the vast majority of soil properties and the functioning of the soil ecosystem. From the functions SOM exerts in the soil ecosystem, to the consequences of its depletion and the possibilities it offers for ecological restoration, this concise opinion offers a perspective on the multifaceted roles of SOM in sustaining ecosystem functioning and the services it generates. Indeed, SOM plays crucial roles in supporting soil long-term fertility and the provision of ecosystem services, such as food, water, genetic, medical and biochemical resources, religious, cultural and recreational values, as well as sequestration of carbon and regulation of climate. These roles foster the view of SOM as an ideal proxy for soil quality and health, and justify the interest in acting on SOM as a mean of enhancing the sustainability and effectiveness of ecological restoration projects. The improvement of SOM to favor the onset of proper ecological dynamics in heavily degraded ecosystems, such as urban, industrial and agricultural soils, can be also coupled to the recovery of useful organic matter from wastes, integrating ecosystem restoration within waste management and sustainable circular economy strategies. Since, ultimately, the sustainability of our civilization depends upon proper ecological dynamics, soil quality rises to a topic of public concern and this opinion aims at providing a reference point of view on the intertwined implications of its preservation on the ecological, economic and social spheres.

Keywords: Ecological restoration; Fertility; Ecosystem integrity; Soil management; Organic amendment

1. Nature: Can We Put a Value on It?

Attributing values to an intangible asset is rather complex: what is the value of wildlife, clean water and air, and healthy soil? The importance of providing, as accurately as possible, a value—one that is socially acceptable and understandable—to the functions and services that nature provides is associated with the desire to simplify decision-making for policymakers [1]. McCauley [2] has argued that valuing ecosystem services is inappropriate because we should protect nature for its intrinsic value; but valuation is often inevitable in socio-economic dynamics, so it is essential to identify the most suitable approaches [3].

Already in the seventies, Westman [4] aimed at demonstrating the significance of linking benefits to the services provided by nature, while also acknowledging the complexities involved. From this point of view, it is compelling to evaluate the value of ecosystem services, striving to quantify the value of nature not just ecologically, but also economically and socially. The recognition of the complexity of the intertwined economic, cultural and social values is increasingly accepted in decision-making, though the approach can be still hardly considered standard practice [3]. A broader approach that explicitly includes non-market values is being developed in many areas, and aims at integrating ecological sustainability, social justice, and economic efficiency into both public and private decision-making processes [5,6].

To give an idea of the complexity of estimating the value of environmental goods and services, techniques as diverse as cost-benefit analysis, production function analysis, travel cost method, hedonic pricing, contingent valuation and replacement/restoration cost have been developed over the years. For example, cost-benefit analysis (CBA) assesses the

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economic efficiency of alternative policies that affect ecosystem services [7], by quantifying their impacts in terms of positive (benefits) and negative (costs) changes in the flow of ecosystem services. Applications of the technique include the one in Van Wilgen et al. [8], who employed CBA to evaluate the costs and benefits of a program aimed at eradicating alien plants from fynbos vegetation in water catchments in the Western Cape Province of South Africa. Their research illustrates how CBA can be applied to measure both the economic and ecological impacts of environmental management programs. The production function (PF) analysis is based on estimating the contribution of an ecosystem service to the production of specific services that are or could be marketed [9], as in the case of drinking water. It relies on production or cost data, which are generally easier to obtain than the data needed to establish demand for ecosystem services [10]. Travel cost method (TCM) assesses individual preferences for non-market goods by associating their consumption with the cost of transportation required to access them [11], but the obtained monetary estimates can be inaccurate [9] and highly subjective [12]. Hedonic pricing (HP) is based instead on the idea that the value attributed to a service depends on its specific attributes [12]. The method requires a set of measurable attributes that can predict the price of a good when it is traded. However, measuring these environmental attributes is not always straightforward, and this can lead to incorrect estimates [9]. Contingent valuation (CV) is based on a hypothetical market in which people are asked, through questionnaires and/or interviews, to state their demand function for a specific environmental good or service [12]. This method has been widely employed for valuing ecosystem services in various contexts, as it is capable of attributing monetary value to goods without exchange value [9]. However, Mitchell and Carson [13] identified technical problems associated with survey design and implementation. Furthermore, the composition and characteristics of the target group, in particular their income and education levels, strongly influence the magnitude of responses [9]. The replacement/restoration cost (RC) technique determines the value of an ecosystem service by calculating the cost of replacing or restoring it after damage, with the aim of reinstating both lost consumer surplus and non-use value [12]. Economists emphasize that monetary values derived using RC approach are only valid if individuals would genuinely be willing to bear these costs in the absence of the natural services [14]. Moreover, the approach is prone to underestimations, due to ecosystem complexity. The ability of soils to absorb air pollutants is an example of ecosystem service whose loss may be undervalued, due to our still limited understanding of the functioning of such a complex ecosystem.

Soils in natural and managed ecosystems are crucial regulatory systems that control a multitude of ecological dynamics with the provision of several ecosystem services [15–18]. They further represent one of the critical factors affecting national economies - that's why the study of soils within the framework of ecosystem services should bear crucial relevance in decision-making and the definition of policies [19]. In this context, the focus on the services provided by soils is an important part of a larger initiative to incorporate all aspects of nature into an economic perspective [20].

Recently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has broadened the notion of ecosystem service by defining 18 Nature's Contributions to People (NCPs) as "all contributions—positive or negative—of living nature (including diversity of organisms, ecosystems and their associated ecological and evolutionary processes) to the quality of human life" [21]. The definition serves as an expansion of the ecosystem service concept, embracing a broader array of fields including social sciences and humanities [22], and categorizes NCPs into material, non-material, and regulation contributions.

Material NCPs are substances, objects or other tangible elements provided by nature, which directly support life and are physically consumed upon their utilization [21]. As summarized by Smith et al. [23], examples of soil involvement in providing material NCPs include its roles in generating food for a growing global population [24], in serving as water reservoirs [25], and in providing genetic, medical, and biochemical resources [26]. Sometimes also referred as cultural NCPs, non-material NCPs denote the intangible effects of nature on subjective or psychological aspects that support the quality of life for individuals and communities [21]. McElwee [27] described the myriad of ways in which soils influence artistic expressions (e.g., literature, cinema) and mental and physical well-being through a wide range of recreational activities. Moreover, these contributions extend also to cultural identities and practices, ranging from religious beliefs and rituals to language and politics. Despite their intricate nature and still vague quantification, soil-provided non-material NCPs are not less important for humanity than material NCPs [23]. Regulation NCPs describe functional and structural attributes of organisms and ecosystems that alter environmental conditions and/or regulate the generation of material and non-material NCPs [21]. For example, it was highlighted the importance of soils in regulating water quality [28] and climate, by acting on source-sink dynamics of greenhouse gases and on water and radiative balances [29].

In this context, the need to preserve soil health is self-evident, lest we forego the invaluable services and contributions it offers while also sidestepping the economic and social repercussions linked to its deterioration. Where prevention is no longer possible and soil degradation is unavoidable, the implementation of restoration strategies becomes in turn imperative. Restoration options for degraded soils include revegetation, reduction of grazing pressure, bioremediation, and recovery or maintenance of soil organic matter (SOM) levels [23].

To date, the role of SOM in controlling the ability of soils to provide ecosystem services and sustaining societies at both global and local levels is well established [30–32]. SOM is recognized as a crucial element affecting soil fertility and crop production, as well as mitigating contamination, degradation, erosion and desertification, especially in arid and semi-arid regions [33]. This is why the correlation between SOM and soil quality is universally acknowledged [34]. Indeed, in spite of the usually poor definition of "quality" when it comes to soil, requiring multiple parameters for unbiased evaluations [35], both the quantity and quality of SOM come remarkably close to ideal and comprehensive indicators of soil quality, since they directly and indirectly affect the physical, chemical and biological properties of soil [36,37].

2. Organic Matter Roles in Soil

Excluding living organisms, from a structural viewpoint SOM consists of any material originally produced by living organisms themselves that returns to the soil and undergoes humification or decomposition [38], driven by abiotic factors and by the activity of heterotrophic microbial communities [39,40]. These processes determine the high reactivity and dynamism of SOM, that can be fed upon by a multitude of different organisms [41,42] as well as consumed and transformed by chemical and physical processes, such as leaching or photo-degradation [43]. Interestingly, in spite of the diverse chemical composition of primary sources, the processes SOM undergoes in soil, mediated by the activity of soil communities, determine the convergence of its composition toward molecules with specific characteristics [44], a process known as the "decomposer funnel" [45]. Among these characteristics, there are [46]: high aromaticity [47], low C/N and C/P [48] ratios, low energy content and high activation energy [49]. In turn, the dynamical characteristics of SOM control microbial community biodiversity and dynamics [50,51], as well as the interaction with the mineral matrix [39,52], ultimately defining SOM functional roles within the soil ecosystem.

From a physical perspective, SOM is able to critically control the entirety of soil properties, such as structure, water retention, bulk density, porosity and susceptibility to erosion [53–55], that are noticeably altered even by small variations in the amount of SOM [37]. Indeed, SOM is able to bind soil particles [56] both directly and indirectly by increasing the stabilizing capabilities of other compounds [57], or by supporting the organisms involved in particle aggregation (e.g., fungal hyphae, roots, micro-, meso- and macrofauna) [39]. In terms of soil chemical properties, SOM contributes to plant nutrition with the release of nutrients in bioavailable forms trough mineralization by microorganisms [58]. Apart from environmental conditions such as temperature, pH, water and oxygen availability, nutrient release from SOM strictly depends on its chemical composition, e.g., the lower the C/N ratio, the more rapidly nitrogen will be released into the soil [59]. Furthermore, the presence of charged functional groups (e.g., oxydril, carboxyl) on SOM molecules promotes cation exchange capacity (CEC) [38], and buffers soil pH [60]. Additionally, SOM is responsible for the adsorption and complexation processes that play a key role in modulating the availability of both nutrients and non-essential elements for plants [61,62].

The capability of SOM to sustain primary productivity and to increase environmental heterogeneity at micro- to macro-scales through soil structuring [63], reflects on its capability to shape the biodiversity of both below- [64,65] and above-ground communities [66], affecting in turn ecosystem functioning. In this context, the common correlation between the below-ground and above-ground biodiversity can be partially explained by the shared relationship with SOM [67]. From these premises, strategies to preserve and increase SOM can be adopted as viable means to enhance soil diversity [68]. Interestingly, the effects can be species-specific, resulting in the differential inhibition and promotion of different organisms. A remarkable example is the observed suppression of plant pathogens with concomitant promotion of saprophytes [69].

3. Loss of Organic Matter and Soil Degradation

By impairing the overall properties and functioning of soil ecosystems, the loss of SOM critically promotes soil degradation [61,70,71], which currently represents one of the most significant issues for 33% of terrestrial ecosystems worldwide [43,72,73]. For instance, it represents a global challenge for agriculture, leading to estimated yearly reductions of up to 33.7 million tonnes in food production [74], increased food insecurity, and prices of agricultural products raising by 0.4% to 3.5% worldwide [75]. From an economy viewpoint, the global loss of ecosystem functions caused by soil degradation is estimated to costs approximately USD 10.6 $\times$ 10^{12} per year [76]. The loss of SOM commonly results from the unsustainable use of soils [77] that leads to their physical, chemical, and biological deterioration, in turn impairing ecosystem functioning and determining substantial economic costs, which affect not only those who directly use soils, but also the society as a whole [78].

The current steady degradation of soils can be traced back to the coupling of several dynamics at global scale, most notably the growing global population and urbanization. The need to feed an increasing number of people concentrated into ever enlarging cities led, on the one hand, to the direct destruction of soils [63] and, on the other hand, to land use changes and the adoption of unsustainable food production practices [75,79]. For example, large swathes of European soils suffer from unsustainable management practices leading to a loss of their ability to provide ecological functions [80]. The spatial separation between food production and consumption alone, determines a reduction of organic matter inputs to the soil in agroecosystems and a progressive depletion of SOM, a process further exacerbated by practices such as intensive tillage, overgrazing and slopeways downhill plowing [81]. The actual rates of SOM loss and soil degradation, however, depend upon a complex interaction among demographic, technological, political, institutional and cultural factors [82]. For example, poverty is usually associated to severe soil degradation, due to rapid population growth, reduced interest in soil conservation in the face of challenging living conditions and low funding for environmental protection [82]. In turn soil degradation promotes poverty due to the increased costs of food production, the likelihood of famine and unstable social conditions, in a vicious cycle binding soil and societal health. Conversely, economic and social development tends to promote people's awareness of the need of soil preservation, promoting conscious lifestyles, the adoption of sustainable soil management practices and of conservation strategies [82].

The effects of unsustainable practices can be exacerbated by climate, as in the Mediterranean region, where soil temperature and moisture conditions accelerate respiration and mineralization, with the depletion of SOM [83]. Global warming is expected to speed up the reduction of SOM, with the concomitant release of more CO_2 into the atmosphere and the further alteration of climate [84]. In this context, the climate-increased frequency of wildfires is also able to promote soil degradation and desertification through SOM oxidation, a phenomenon, however, highly dependent upon temperature and fire residence time [85]. As a further testament of the intricate relationships between climate and soil quality, the Intergovernmental Panel on Climate Change (IPCC) provides its own precise definition of land degradation: "a negative shift in land condition due to direct or indirect human-induced activities resulting in a long-term reduction or loss of biological productivity, ecological integrity, or human value" [86].

The paradox of land degradation, as most other forms of ecosystem alterations, lies in humans being both the main cause and the main victim simultaneously. However, by restoring SOM levels, humans can also contribute to the solution [87].

4. Ecological Restoration through Organic Amendments

Ecological restoration represents the process of assisting ecosystems in the recovery from degradation, damage, or destruction [88]. The earliest evidence of ecological restoration projects dates back to biblical times, with fallow land [89]. In modern times, restoration has been used in a variety of ways to achieve a broad range of policy objectives. In the context of global environmental change, ecological restoration is increasingly being applied to restore ecological integrity and the provision of ecosystem services, resulting in large involvement of decision-makers in restoration initiatives [89]. Restoration activities can target a wide variety of ecological systems through the application of different recovery strategies. In terrestrial ecosystems, this is usually achieved by focusing on the recovery of plant communities, due to their crucial control over ecosystem dynamics such as energy flow, hydrology, soil stability, habitat heterogeneity and spatial connectivity. In turn, such an outcome can be achieved through the recovery of soil ecosystem integrity and of the associated fertility, that commonly means acting on the replenishment of SOM through organic amendments [66].

Organic amendment refers to the practice of adding heterogeneous sources of organic matter to the soil, with the aim to maintain or recover soil physical, chemical, biological, and ecological functionality [90]. This approach encompasses various methods, from mulching to the application of products derived from organic wastes, biofertilizers and soil conditioners, varying in the concentration and composition of organic matter inputs and in their effectiveness [71]. Originally developed as strategies to improve the fertility of agricultural soils [91], organic amendments are increasingly being proven as viable and sustainable means to restore degraded soils and promote vegetation recovery in a variety of different ecosystems [92,93]. In addition to materials containing pools of available nutrients, such as compost or stabilized manure, alternatives that may not directly function as fertilizers in the short term, such as woody biomass, straw and other plant residues, are also useful to build up soil carbon stock and lower greenhouse gas emissions. Moreover, acting as soil conditioners, they contribute to improve soil structure and aggregate stability, due to the formation of new complexes between soil particles and organic matter [94,95]. Consequently, they indirectly improve porosity, bulk density, water retention, microbial biomass, activity and diversity and even reduce the bioavailability of both organic and inorganic contaminants, with positive effects on fertility [39,90,94,96–101]. However, the negligible effects of conditioners on fertility and, in general, on several ecosystem processes in the short term, question their effectiveness whenever such actions are crucial for a quick recovery and support of ecosystem integrity [102]. In this context, the abundance of labile carbon pools and available nutrients in urban, industrial and agricultural raw wastes make them, instead, potentially useful as organic amendments [103] for the rapid enhancement of soil fertility. However, the presence of contaminants and pathogens, as well as the possible phytotoxic effects and microbial immobilisation of nutrients severely limit their applicability [104]. Humus-like substances derived through the processing of organic wastes, instead, can be especially promising, but their characteristics are highly variable in relation to the source material and should meet strict requirements in terms of being free from contaminants, pathogens and phythotoxic effects [103–105].

The differential effects elicited by different kinds of organic amendments underpin the importance of taking into account the type of organic inputs [106,107], rather than merely focusing on SOM levels in restoration actions. Indeed, the long-term increase in SOM levels depends on the persistence in soil of humified compounds, whose production does not follow a regular pattern and is strongly influenced by the source material in addition to weather and climate [108]. The presence of lignin and cellulose, in particular, plays a crucial role in influencing this process and in building-up persistent SOM pools [109]. Usually, a noticeable increase in soil organic carbon becomes apparent gradually, several months after the first application [110]. In this context, the direct addition of organic matter containing humus-like molecules, such as compost, or recalcitrant carbon structures, such as biochar, can significantly reduce the time necessary to build-up persistant SOM pools.

Several successful ecological restoration programs have been implemented in different countries. Since 2012 China has made several efforts in this regard, resulting in the regeneration of many hectares of degraded land to restore plant communities and enhance soil carbon sequestration [111]. In Iceland, documented restoration activities dates back to 1907, with 1800 Km^2 of restored area up to the 2010 and the Soil Conservation Service of Iceland (SCSI) being one of the main actors in this process [112]. In the Mediterranean area, The Restoring Mediterranean Forests Initiative consists of an innovative approach to protect and restore vulnerable ecosystems and has restored approximately two million hectares of forests in Lebanon, Morocco, Tunisia and Turkey since 2017 [113]. The Accion Andina movement, led by the Association Ecosistemas Andinos (ECOAN), aims to protect and restore one million hectares of forest in South America to preserve the forest from different drivers of degradation [114]. These are just a few examples of a movement that has become increasingly important globally in recent decades and will continue to be relevant in the future. In this context, however, long-term studies on ecosystem restoration trough SOM preservation/increase are crucial, since the recovery dynamics can unfold over several years. For example, while organic amendments are able to increase SOM in a short to medium time span, the effects on soil structure, hydrological regulation, vegetation growth and biodiversity can be appreciated over longer time spans [94]. Moreover, the clarification of long-term dynamics holds significant social importance, as landowners often harbor skepticism towards soil management practices that do not provide immediate benefits [115].

5. Remarks and Perspectives

Soil health and fertility represent both the basis for and the result of sustainable social, economic and political processes [116]. Understanding the roles of SOM in promoting these processes facilitates the development of sustainable management strategies capable of restoring and preserving ecosystem integrity. The temporal horizon for these strategies should embrace not only the short term, but especially the long term support for the provision of ecosystem services from soils. Indeed, while farmers may be interested in adopting practices to maintain and improve SOM content with the goal of enhancing productivity, these actions should be included and organized into broader objectives of ensuring food security for a rising global population, maximizing economic returns, promoting nutritional diversity and conserving soil and water resources for future generations [63,116].

It's not easy to determine general rules for including the management of SOM into these long-reaching objectives, because they depend not only on soil and climate factors, but also on social, economic and political contexts that are inherently heterogeneous among different nations and within them. As such, strategies to recover and preserve soil ecosystem integrity require the involvement of subjects acting at different levels, from land-owners acting at small scale, to citizens and entrepreneurs able to shape market dynamics, to researchers providing solid information, to policy-makers defining large scale (spatial and temporal) goals. Indeed, there is a pressing need for coordination among subjects involved in soil management to establish effective communication channels, promoting the tackling of the complex and interdisciplinary soil issues [117]. This is ever more crucial in the context of adapting policies to the changing global conditions [118] and, especially, the current geopolitical shifts and realignments.

"We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect." — Aldo Leopold, A Sand County Almanac, 1949

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