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Review

Organic amendments for soil restoration in arid and semiarid areas: a review

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Abstract: The use of organic amendments produced from organic waste has been widely studied. Not much is known, however, about the use of such amendments for restoring abandoned or degraded soils in arid and semiarid areas that could serve as good carbon sinks. Such soils have scarce vegetation and organic matter but contain a variety of microorganisms adapted to different types of stress. The characteristics of "organic amendments" depend on their origin (urban: domestic organic waste and sludges from urban wastewater treatments; other: animal (manure), agricultural or agroindustrial) and determine in part their potential positive or negative effects on the soils they are applied to. The way amendments have been treated (e.g., composting) also determines how they will behave in the soil. This review covers the last 15 years of published research concerning the use of organic amendments on degraded soils in arid and semiarid environments for restoration purposes.

Keywords: organic amendments; organic wastes; soil restoration; management of organic wastes; arid-semiarid conditions; degraded soils

1. Soil Degradation and Organic Matter in Arid and Semiarid Areas: Importance

Soil is a natural resource that provides ecosystem services critical for life. Soil provides the medium for plant growth, is the habitat for billions of organisms, contributing to biodiversity, act as a filtration system for surface water, and helps regulate atmospheric carbon dioxide by acting as a carbon store. Soil is the foundation for our cities and towns and it is the basis of our agrosystems that provide us with fibre, feed, food and fuel. Summarizing, soil is necessary for the sustainability of humankind, this explaining the necessity of its protection and conservation.

Mol and Keesstra [1], in a recent publication, highlighted the necessity of a greater communication between soils scientific as well as between soil scientific, the society and governments in order to solve soil related problems such as food security, water resources, biodiversity, and climate change. These authors also indicated that the link between soil research and knowledge, and effective human action depends to a large degree on the right political and administrative interventions. In this sense, the United Nations have proposed several goals to achieve ecosystem sustainability, highlighting how the soils are relevant to achieve these goals [2].

Soil degradation is a serious problem, particularly in arid and semiarid areas, characterised by low and erratic rainfall, periodic droughts and different associations of vegetative cover and soils [3]. In these areas both, human-induced actions and natural conditions contribute to the loss of soil organic matter (SOM), which is strongly linked to soil degradation and desertification, and causes a decline in agronomical productivity and the failure of soil ecosystem services [4]. Arid and semiarid ecosystems have little vegetation and hence lower carbon accumulation than other ecosystems; however, they are estimated to contain 20% of the global soil C pool (organic plus inorganic) in continental areas [5]. Lal et al. [6] concluded that the predicted amounts of carbon in drylands are between 159 and 191 billion tons, with a density of 35 to 42 tons C ha^{-1}. Since carbon in arid and semiarid climates has been depleted for both “natural” and “anthropogenic” reasons, these soils still have the capacity for carbon sequestration, which can increase soil quality, ensure food security and mitigate global climate change [7].

One important characteristic of the soils of the arid and semiarid regions is that they have a low organic matter content and that they are submitted to erosion and desertification processes [3]. The loss of organic matter and the degradation of soil structure are closely related with the loss of its agricultural potential and with an increasing risk of erosion. This can imply a diminution or destruction of the soil’s biological potential, leading in extreme conditions to desertification [3,7].

Intensive cultivation, continual ploughing and forest fires, allied to years of unsuitable agricultural practices, have had a detrimental effect on humification processes and on properties associated with degradation. All the above has led to a great diminution in the quantity of vegetal remains returned to the soil, while the humus is undergoing a process of accelerated mineralisation as a result of tilling. The inevitable result is a progressive diminution of the soil’s organic matter content and the entailed negative consequences. These activities can have a negative impact on the soil, preventing it from performing its broad range of functions and services benefitting humans and ecosystems. Soil degradation results in a loss of soil fertility, carbon and biodiversity; a lower water-holding capacity; disruption of the gas and nutrient cycles; and reduced degradation of contaminants [8]. Moreover, since the adoption of the 2002 Communication on soil protection [9], an effort has been made to ensure that recent environmental policy initiatives in the EU concerning waste, water, air, climate change, chemicals, flooding, biodiversity and environmental liability also contribute to soil protection. In particular, the Environmental Liability Directive [10] created a coherent framework of liability to be applied across the EU in situations where land contamination has resulted in a significant risk to human health.

The close relationship between a soil’s organic matter content and its fertility is widely accepted. The organic matter improves soil aggregate stability and structure and increases its porosity and water holding capacity, thus favouring gas and water exchange and the exploratory capacity of plant roots. The cationic exchange capacity is increased which favours nutrient fixation, maintaining them longer at the plant disposition and increases the development of its microbial flora [11].

One way of improving the fertility of degraded soils and particularly of improving its microbial activity, is to add "young" exogenous organic matter. By this term we mean that the amendment must contribute to provide labile organic matter in sufficient quantity to stimulate the life of the microorganisms that might exist in the soil. To this purpose, organic amendments are appropriate source of organic matter. The characteristics of these products determine that they have a good behaviour in the soil from a physical point of view (increase soil sponginess), they contribute to improve the nutritional quality of the soil and, most importantly, their labile organic fraction acts as a catalyst for the microorganisms, improving in this way the potential soil fertility and the biogeochemical cycles of the most important elements.

Soil organic matter plays a key role in the development and functioning of terrestrial ecosystems, so both the quality and the quantity of SOM are quite important. SOM quality is related to the process involved in its formation (humification) and the material from which it comes. Regarding quantity, the amount of SOM in the soil should be nearly constant, a balance between input from either animal or plant debris (part of this fraction goes to humification) and organic matter losses, producing H_2O and CO_2 (the mineralisation process) [11]. When the equilibrium between these two complex processes (humification and mineralisation) is broken by some action that harm the soil, a negative loss of organic matter takes place, which leads to decreases in soil fertility and productivity. Owing to the close relationship between soil organic matter content and soil fertility, it is fundamental to maintain an adequate level of organic matter in soils. To accomplish this, it is essential to search for new sources of organic matter to restore the SOM lost due to inadequate land management practices.

Lal [12] indicated that the pool of organic matter in soils worldwide has decreased 25–75%, depending on climatic conditions, soil type and soil management practices. Such decreases in the soil C pool lead to a decline in production capacity and the ability of the soil to sequester CO_2 from the atmosphere through the biochemical cycles. Lal [7] has proposed some measures to promote C fixation in the soil so that soils can be used as C sinks, counteracting the effects of global warming. These measures include: (1) the restoration of degraded soils; (2) the development of sustainable agriculture; (3) the use of suitable plant species adapted to the environmental conditions of specific sites; and (4) good management of cover crops. There are three main mechanisms for the stabilisation of organic C in soils. The first is biochemical stabilisation, which is due to the chemical composition of the C pool in a given soil and is closely related to microbial activity. The second mechanism is physical stabilisation. When aggregates of organic matter are formed, a protective system is created, hindering biological degradation. Finally, the third mechanism is chemical stabilisation, which occurs through molecular interactions between organic C and mineral colloids (mainly clay and lime). Aggregates protect SOM from microbial attack (mineralisation process) and thus increase the average residence time of C in the soil [13]. According to Kalbitz et al. [14], the organic C associated with fine soil fractions (silt and clay) stays longer in the soil than the C associated with greater size soil particles. Six and Jastrow [15] and Pulleman and Marinissen [16] agree that soil aggregates are able to protect soil organic C and that the oldest organic C fractions are located in soil micro-aggregates. Organic matter affects soil characteristics, but the organic matter present in aggregates plays the greatest role in soil functionality.

2. Organic Amendments: A Strategy for Soil Restoration in Arid and Semiarid Areas

Among all the different types of generated wastes, biological organic wastes represent one of the most environmentally significant since they are continuously and globally produced. The moment the environment waste absorption capacity is surpassed, the problem of contamination arises, which may have serious economic consequences. It seems clear then, that society must turn its immediate attention to the problems that wastes provoke and offer suitable solutions. Attempts must be made to give them a value so that they represent as low an economic burden as possible while minimising negative environmental effects and guaranteeing sustainability. As the main alternative for the above-mentioned wastes we propose their recycling in the soil, which will achieve a double aim: on the one hand, a good use is made of an organic waste (assuming of course the proper and orderly control of the process) than otherwise will create environmental problems, and on the other hand, their rational use will contribute to prevent soil degradation and desertification in those places where the organic matter is deficient, thus improving soil quality [11].

In this respect, based on present day scientific knowledge, the recycling of organic amendments in soils have a benefit (added value) by: (1) recovering soils that are degraded through anthropic activities or natural disasters, particularly in arid and semiarid zones where soil degradation processes are very strong; (2) evaluating the effectiveness of organic wastes in sequestering C, contributing to mitigate the greenhouse effect; (3) obtaining organic amendments and improving the biodiversity of the soil to which they are added. This is fundamental to combat processes of soil degradation and to promote soil fertility recovery; (4) using organic amendments as "support" for the decontamination of contaminated soils, and for rehabilitating saline soils.

In natural soils, there is a balance between the C provided by the existing vegetation (inputs) and the natural mineralization produced by the microbial activity in the soil [17,18]. In arid and semiarid zones, there is minimal vegetation due to climate conditions and the resulting scarcity of water and thus, insufficient C inputs [11]. In such environments, agricultural productivity and fertility are compromised by the fact that the soil is poor in organic matter [19,21]. The use of organic amendments as a source of exogenous organic matter could be an adequate strategy for maintaining soil fertility in such degraded soils [11]. All the processes described above are clearly detailed in Figure 1.

2.1. Organic Amendments for Agricultural Systems in Arid and Semiarid Areas.

Agricultural systems in arid and semiarid zones consume a large quantity of agrochemicals in order to maintain soil fertility and productivity. In addition to this, climate change, soil overexploitation and soil contamination (salinization, etc.) can seriously impair soil productivity and fertility, resulting in the abandonment of such soils [22,23]. In turn, abandonment can lead to processes of degradation and desertification, since vegetation rarely takes root in such conditions, resulting in minimal C input.

In agricultural systems, both organic fertilizers and organic amendments of different origins have been proposed for improving and alleviating the scarcity of organic matter in such soils. Although agricultural systems are not the main subject of this review, we will consider certain relevant aspects of the field. Climate change poses an important challenge for food production, and global warming and the lack of water have endangered agricultural systems, especially in semiarid climates. According to Komatsuzaki and Ohta [24], there is clear evidence that continuous cropping and inadequate replacement of nutrients in the soil, which are removed along with harvested materials or lost through erosion, leaching and gaseous emissions, are degrading soil physical, chemical and biological properties, intensifying global warming. In this situation, agriculture must meet the goal of ensuring productivity by effectively adapting to changing climatic conditions while at the same time mitigating their harmful consequences; in other words, agriculture has to be more resilient [25]. To achieve the goal of a better agriculture, the quality of the soil used for agricultural purposes must be preserved or enhanced through new sources of fertilisation [26]. In accordance with Lal [7] and Diacono and Montemurro [27], agricultural management practices that enhance SOM content can preserve both, farming output and environmental quality. Such practices are considered sustainable activities and should be encouraged in agricultural soils. An interesting alternative to traditional mineral fertilisation for improving soil quality is the application of organic wastes, such as by-products from farming or municipal activities, including animal manures, food processing wastes and municipal biosolids [27]. The application of organic wastes has been widely shown to be an adequate strategy for increasing the level of organic matter in soils, with benefits for the development of soil microorganisms and plants [28,29].

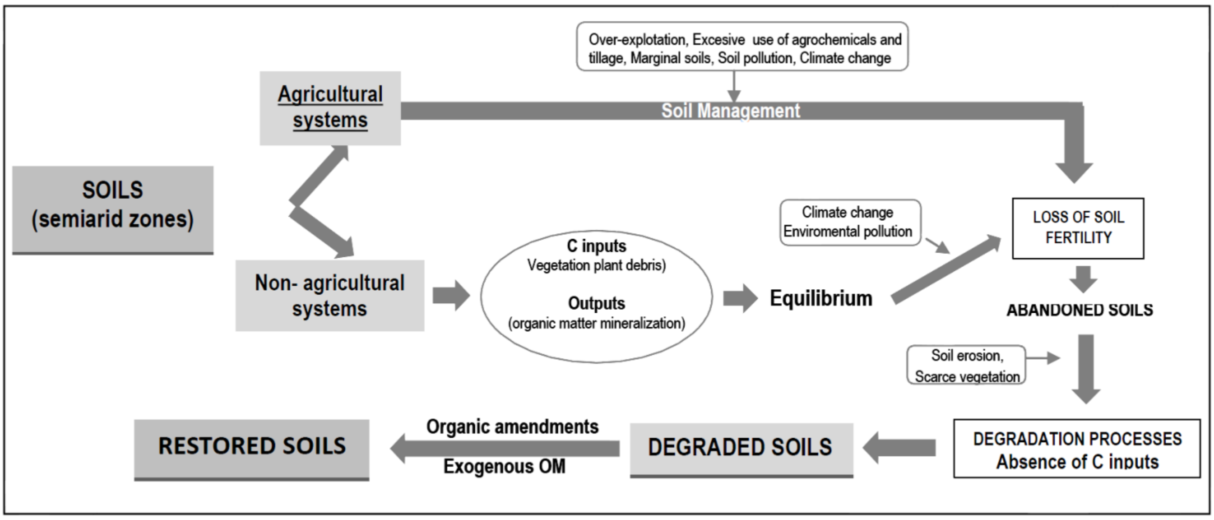

Figure 1. Soil degradation and restoration in semiarid-arid areas

By way of example, Antolin et al. [30] evaluated the effects of sewage sludge on the growth and yield of barley under semiarid Mediterranean conditions for a period of four years. Barley grain yield increased significantly under repeated sewage sludge application. Moreover, sewage sludge addition improved soil microbiological properties and increased protein concentration in barley leaves as well as the dry matter yield. The results further indicated that under Mediterranean climatic conditions it was possible to maintain crop production by the continuous annual addition of sewage sludge at low dose (15 t/ha). However, they also detected significant increases in the concentration of heavy metals in barley grain which suggests that care should be taken in long-term application of sewage sludges. In similar experiments, increases in soil fertility were observed with the application of the following organic amendments: sludges, pre-treated wastewater, manure, compost and industrial effluents. In these studies, researchers found that the application of these organic amendments enhanced extractable phosphorous and organic C content and resulted in deferred N availability, indicating an increase in nutrient content and soil fertility [27,31,32].

Sustainable practices with the addition of organic amendments (soil management) could be a useful tool for maintaining and even increasing the organic matter content in agricultural soils, thus preserving and improving soil fertility [33,34]. There is a clear need for sustainable systems, because intensive agriculture practices in soils already poor in nutrients have further reduced soil quality and fertility, resulting in land abandonment and soil degradation [21,35]. Many agricultural soils are very susceptible to environmental degradation and are thus unsuitable for crop production. This is particularly true in the Mediterranean region, which has large areas of low quality degraded soils with little plant cover and organic matter content. Furthermore, the traditional sources of organic matter (peat and manure) are scarce in extensive areas of Europe, particularly in southern Europe. To counteract this situation, the organic matter contained in organic wastes, sewage sludges, animal manures and other organic residues has begun to be used as a source of SOM. The goal of using such organic matter is twofold since it not only improves the quality and fertility of degraded soils but also simultaneously eliminates organic waste in a rational and environmentally friendly manner [21].

In semiarid areas of southern Ningxia (China), Zhang et al. [36] investigated the effects of different rates of straw incorporation on soil aggregates. The results showed that straw addition increased the water-stable macroaggregate level and stability as well as the storage of organic C compared to the non-amended soil. In general, organic wastes improve soil physical characteristics, promote a good soil structure and improve aeration and water holding capacity [37,38]. Organic wastes also represent an important source of nutrients for plants and microorganisms and thus improve crop production [39,40]. The beneficial effect of adding organic amendments on crop yield and quality has been widely reported [41,42], and can be explained by the significant role played by organic matter in soil aggregation and other soil physical (water holding capacity, infiltration capacity, porosity etc.,) and microbiological properties, as well as to the capacity of organic amendments of slowly releasing nutrients [18,43-45]. Compared with inorganic fertilisers, organic fertilisers have the advantage of continuing to improve the soil long after the plants have taken the nutrients they need [41]. The use of organic fertilisers in place of inorganic fertilisers could reduce the emission of greenhouse gases into the atmosphere. It is important to keep in mind that the organic matter contained in organic fertilisers must be mineralised by soil microorganisms to release nutrients into the soil. This is a slow process depending on the organic waste characteristics and the type of soil and environment (soil water content, temperature) [46].

Several researchers [47] have indicated lower production levels under organic cultivation than under conventional cultivation. Hernández et al. [21] showed that a combination of compost and inorganic fertiliser produced higher yields and better fruit quality than the respective inorganic treatment when used alone. In addition, the soils treated with combined fertilisation showed higher values of microbial biomass C, basal respiration and dehydrogenase activity than the soils subjected to the respective inorganic treatment.

2.2. Organic Amendments for Abandoned and Eroded Soils in Semiarid and Arid Areas

Annually, the global rate of erosion is about 75 billion Mg, and in severely eroded soils, the figure reaches 100 Mg ha^{-1} [48]. Erosion is especially problematic in semiarid areas, where the SOM content is often lower that 1–2%, making it necessary to increase this content by the addition of external sources of organic matter.

There is a wide variety of exploitable organic matter sources (urban, agricultural or animal origin) that can be used to correct the lack of organic matter in soils, especially in semiarid areas. Taking into account the huge amount of organic residue generated worldwide by human and industrial activities, this is a valid option to consider in restoration strategies. Municipal waste materials are often incinerated or taken to landfills, but they could be recycled by amending eroded and degraded soils [49,50]. As an example, sewage sludges (i.e., biosolids) are generated in large amounts in wastewater treatment plants, and their high nutrient content [51] makes them good candidates to be used as soil amendments. Indeed, biosolids have been land-applied to increase the organic matter and nutrient content of soils and to stimulate soil microbial communities [52]. However, domestic waste composition and treatment differ depending of the country; domestic organic wastes can be source-separately collected or mechanically treated to obtain its organic fraction; also, wastewaters can be treated by aerobic or anaerobic digestion thus producing sewage sludges of different quality as regards their use in agriculture or soil restoration processes.

The most used organic amendments include biosolids, farmyard manure, compost from municipal organic waste, sewage sludges, olive mill waste, pulp sludges, wood waste and by-products from ethanol production processes. Additionally, pulp sludges and wood waste have also been used as slope stabilisers or as bulking and structural agents, respectively. These residues need to be submitted to sanitisation processes, such as composting, vermicomposting, or anaerobic digestion, in order to stabilise their organic matter and to control pathogens [53]. Many municipalities have started composting municipal solid waste (MSW) made-up of kitchen and yard wastes [54], thus diverting organic waste materials from landfills while creating a product suitable for agricultural purposes at a relatively low cost [55]. Biological waste valorisation methods like composting are considered to be promising waste management strategies for stabilising organic waste and are an option for treating sewage sludges and municipal solid wastes [56]. Such processes transform waste organic matter into stable humus-like substances that can be used as organic amendments in agriculture. The composting of dewatered sewage sludges (i.e., biosolids) and other organic wastes has been extensively studied and tested at the field level [56,57]. Municipal solid waste (MSW) compost, for example, has been found to have high water holding capacity because of its significant organic matter content [58]. The incorporation of MSW compost into soil has shown to increase microbiological activity and soil fertility [59] by activating the mineralisation processes of the soil. Studies measuring microbial biomass C and related enzyme activities provide very useful information about the biochemical processes occurring in amended soils. Indeed, there is growing evidence that soil biological parameters are early and sensitive indicators of soil ecological stress and of the feasibility of the restoration process [3,35,60].

Over the years, there has been an increase in the use of organic biofertilisers, or biostimulants, obtained from different organic materials by hydrolysis reactions. These biostimulants, generally comprising peptides, amino acids, polysaccharides, humic acids, phytohormones, etc., are directly absorbed by soil microorganisms and plants, which spend a smaller amount of energy in the absorption process [61]. Biostimulants are added to the soil with the aim of encourage and stimulate plant metabolism and reduce stress [62,63] and it has been reported that they stimulate plant growth and enhance the quality and production of the fruit or grain harvested [62]. Research suggests that the application of biostimulants to degraded soils can quickly improve soil's microbial characteristics favouring the development of plant cover and enabling soil restoration [64].

Soils in semiarid areas have very low microbial activity [65], low levels of microbial biomass and low organic matter content (0.5–2%). In this regard, organic amendments of different nature have been used for degraded soil restoration. As an example, Calleja-Cervantes [26] observed significantly higher organic matter content and total N, P and K contents in soils amended with different organic wastes (such as pelletized organic compost made from plant, animal and sewage sludge residues; a compost made from the organic fraction of municipal solid waste; and a compost made of sheep manure) than in the control soil.

Sewage sludges are commonly used as organic amendments in soil restoration initiatives; they contain macronutrients, which are a good source of plant nutrients, while the sludge organic constituents provide beneficial soil conditioning properties. The application of sewage sludges to the soil makes it possible to recycle nutrients reducing the need for commercial fertilisers on cropland. As a drawback, sewage sludges may also contain harmful toxins such as detergents, various salts and pesticides due to effluents from municipal and industrial premises, and toxic organics and hormone disruptors, whose presence in the treated sludge depends on the sludge origin (urban wastewater or industrial water).

Nowadays, the idea that applying biochar can lead in the long-term to the creation of a sink of C in the soil, thereby mitigating climate change and contributing to the restoration of degraded agricultural soils is gaining adepts [66]. Biochar provides an excellent habitat for beneficial soil microbes [67] that aid in enhancing soil fertility and crop productivity [68] due to greater soil aggregation, protecting both the biochar and SOM from degradation [66]. In addition, biochar has also shown to reduce organic and inorganic contaminant toxicity and increase soil pH. This can have positive effects on the soil microbial community and can reduce exposure to contaminants by slowly releasing nutrients over time [69]. Although biochar is considered to be a potential C-sequestering tool, there are contradictory reports about the beneficial effects of biochar, particularly in terms of ecological needs. Currently, there are insufficient data in the literature to draw conclusions about the application and performance of biochar in different soil conditions, such as hypersaline and sodic soils [70]. Nevertheless, Novak et al. [71] observed that the addition of biochar to a coastal soil at dose of 2% decreased soil acidity and S and Zn contents while increased organic C, Ca, Mn, and P contents enhancing soil fertility. Laird et al. [72] also found that biochar improved the fertility of agricultural soils by reducing nutrient leaching (N and P) and soil acidity and increasing soil water retention and cation exchange capacity. Contrarily, other authors have pointed out that biochar additions do not always have a beneficial effect on agricultural soils and crop production [70]. The main potential features of biochar in the soil include the following: biochar can contain toxic compounds such as heavy metals or PAHs than can be released in the soil; it can produce an increase of soil pH and electrical conductivity, as well as an oversupply of nutrients and the binding and deactivation of agrochemical; biochar can also affect soil biological processes and alter microbial community structure and diversity [70]. Regarding the influence of biochar on soil microbial characteristics, some authors have observed differential patterns in relation to changes in community composition and the diversity of bacterial, fungal and archaeal populations [73-76], revealing that different microbial groups respond in different ways to biochar additions.

In recent studies, Hernández et al. [21] and Nicolás et al. [77] evaluated the mid-term impact of adding large amounts of an organic amendment on the recovery of the physical, chemical and, particularly, the microbiological properties of a marginal semiarid degraded soil and on increasing the soil organic C pool. A spontaneous vegetal cover developed on the amended soils 3–4 months after the addition of the organic amendments (compost), and the compost-amended soils showed higher concentrations of organic C than the control soil throughout the experimental period. However, compost addition also increased soil electrical conductivity and nitrate concentrations, particularly at the higher dose. Likewise, compost addition produced an increase in soil heavy metal concentrations, although the levels of heavy metal were under the limits allowed in soils in the EU.

2.3. Organic Amendments and Soil Erosion

Among the different processes leading to soil degradation, erosion is one of the major problems at European level. Thus, 26 million hectares in the EU are affected by water erosion and 1 million hectares by wind erosion. In the Mediterranean area losses of between 20 and 40 Mg ha^{-1} of soil have been estimated after a storm, and even up to more than 100 Mg ha^{-1} in extreme events. This erosion, which is initially superficial laminar, if not stopped in time ends up being furrowed, ending in the formation of gullies and ravines.

According to Lal [78], soil erosion affects soil organic carbon dynamics through its impact on: (1) slaking or disruption of aggregates; (2) preferential removal of C in runoff water or dust storms; (3) mineralization of soil organic matter on-site; (4) mineralization of soil organic carbon displaced and redistribution over the landscape and transported in rivers and dust storms; (5) re-aggregation of soil trough formation of organo-mineral complexes at the depositional/protected sites; and (6) deep burial of C-enriched sediment in depositional sites, flood plains and reservoirs and ocean floor.

According to Krull et al. [79], soil erosion processes can negatively affect the different C pool existing in soil, particularly the soluble C pool. Three different C pools with different turnover times could be affected by soil erosion process: (1) the active or labile pool also named “sensitive” [80], consisting of microbial biomass, and plant detritus with a turnover time of about 1–2 years; (2) the intermediate or slow pool with a residence time of about 10–100 years, consisting of recalcitrant organic compounds and physically protected organic matter; (3) the passive pool, consisting of very old material that is physically or biochemically protected, with a turnover time of about > 100 years.

The conversion of natural ecosystems to pasture can lead to high rates of erosion and loss of topsoil, nutrients and carbon. Overgrazing can reduce ground cover, enabling erosion and compaction of the land by wind and rain. This reduces the ability for plants to grow and water to penetrate, which harms soil microbes and results in serious erosion of the land. The loss of fertile soil makes land less productive for agriculture, creates new deserts, pollutes waterways and can alter how water flows through the landscape, potentially making flooding more common. Desertification can be characterized by the droughts and arid conditions the landscape endures as a result of human exploitation of fragile ecosystems. Effects include land degradation, soil erosion and sterility, and a loss of biodiversity, with huge economic costs for nations where deserts are growing.

There are strategies of soil restoration that contribute to avoid soil erosion and C losses. For instance, the promotion of sustainable agriculture practices is fundamental. Farming is the world’s largest industry, employing a billion people who produce more than one trillion dollars of food annually. We should promote the use and development of sustainable agriculture that preserves and restores critical habitats, helps protect watersheds and improves the health of soil and water. Also we should work to reduce deforestation that is a factor causing soil erosion [81]. Given the amount of deforestation around the world, zero net deforestation may seem unattainable. However, we should maintain critical ecosystem services and reduce greenhouse gas emissions. Some nations are already conducting successfully, like Paraguay that reduced the rate of deforestation by 85% the year after its 2004 zero deforestation law (WWF).

The inherent climate conditions and erosion rates, together with the advent impacts of climate change and the direct agricultural-mediated human impacts might cause a loss of soil organic C that is strongly related to soil degradation in arid and semiarid areas [3]. For this purpose, organic amendments constitute a source of organic matter (exogenous organic C), and it is a good strategy for soil restoration, and to counterbalance the scarce input from plant debris in degraded soils [11,82,83]. In addition, when organic amendments are added to eroded and degraded soils, some initial spontaneous vegetation from some weeds can be generated, which lead to the incorporation of new biomass carbon to the soil Many studies have shown the benefited impacts of organic amendments on soil quality with environmental perspectives [11,28,53,84-88]; in addition, in the case of very badly degraded and eroded arid soils, organic amendments could help to promote the formation of soil crusts as a preliminary stabilization step.

2.4. Organic Amendments for Polluted Soils in Semiarid and Arid Areas

The EU integrated pollution prevention and control (IPPC) [89] strengthened soil protection and contamination prevention on the basic obligation to avoid pollution risk, return IPPC installation sites to a “satisfactory state” and periodically monitor polluted soils. The use of organic amendments to restore degraded areas was emerging to aim with EU proposals. As a result, organic amendments have been used for soil restoration purposes in several areas, including in soils polluted by organic substances, pesticides and mining activities. Among the organic contaminants, polycyclic aromatic hydrocarbons (PAHs) are critical pollutants [90]. PAHs are produced by incomplete combustion and pyrolysis of organic matter and arise in the environment from natural (e.g., forest fires and volcanic eruptions) and anthropogenic (e.g., vehicular emissions, residential wood burning, petroleum catalytic cracking, and industrial combustion of fossil fuel) sources [91,92]. These pollutants are of great concern because of their adverse health effects, such as toxicity, mutagenicity and carcinogenicity. Although PAHs in soil may dissipate via volatilisation, photolysis, plant uptake and soil sorption processes, their major dissipation pathway is microbial degradation, as they can be used as a C source by microorganisms [93,94]. Fungi and bacteria can metabolise hydrocarbons and either complete their mineralisation to carbon dioxide and water or at least transform the pollutants into harmless products. Given the ability of microorganisms to degrade hydrocarbons it is possible to use biological methods (e.g., bioremediation and phytoremediation) to remediate hydrocarbon-contaminated media [95]. In fact, a large number of studies have demonstrated the degradation of PAHs through bioremediation practices [96-99].

Contamination due to organic compounds has been extensively studied. For instance, Gan et al. [100], reviewed the remediation of soils contaminated with polycyclic aromatic hydrocarbons (PAH). Soil and water contamination with petroleum-derived hydrocarbons and sludge generated by the petrochemical industry pose drastic environmental problems [101]. However, the addition of organic amendments increases the metabolic activity of soil microflora and contributes to hydrocarbon degradation [102].

Restoration initiatives have also tackled the environmental fate of certain pesticides in the soil. It has been reported that the addition of municipal solid waste compost to soil significantly increases the absorption of pesticides, such as triasulfuron [103], chlorophenol biocides and dichloro-diphenyl-trichloroethane (DDT) after the addition of spent mushroom composts [104]. Other authors have also obtained good results with the addition of farmyard manures [105].

In the field of restoring abandoned mining soils, alternative remediation methods are encouraged by environmental managers to avoid onerous investments in site remediation. Amending impacted soils with organic materials improves soil physicochemical properties (e.g., increasing porosity to air and water), providing an organic substrate (C, N, and P) for the proliferation of soil micro-flora, which is the basis for remediation success, and to promote soil revegetation [106]. Data reported in the literature demonstrate that different types of industrial or municipal wastes can be used to successfully remediate disturbed soils [107-109]. Sewage sludges can be used in restoration initiatives for establishing a productive rhizosphere and obtaining an extensive and healthy vegetation cover [108]. Nevertheless, sludges that are not fully stabilised are considered immature and may contain high levels of ammonia and volatile fatty acids. To the contrary, the use of stabilised sludges (composted or anaerobically digested) is highly encouraged for soil restoration purposes, since the humification process during sludge stabilisation helps ensure that metals are less bioavailable and thus less ecotoxic in the resulting sludge [110]. Certain phytoremediation technologies can also be applied to reduce the heavy metal concentration in soils. Such metals are persistent contaminants that cannot be biodegraded, but they can be treated by phytoextraction or phytostabilisation [111].

Heavy metal pollution is an important factor in land degradation. This pollution could come to soils due to the increase of human activities (e.g., mine industries, agriculture use of organic amendments with high charge of heavy metals). On fact, the European Union shows about 250 000 polluted sites [112] where specific strategies for restoration could be adopted. Heavy metal contamination strongly affects the structure and functioning of ecosystems [113].

One important concern is the absorption of heavy metals by crops. Hseu et al. [114] reviewed heavy metal uptaking in different plant varieties and remediation technologies and they concluded that it is necessary to identify the bioavailability of heavy metals in different soil types from specific case studies to provide reliable parameters for health-based risk assessments and to further achieve the goal of food safety and sustainable agriculture. In this sense, Pardo et al. [115] indicated that phytostabilization and organic amendments may reduce the amount of available heavy metals and benefits soil functionality. Soil microbial biomass is greatly sensitive to heavy metal concentration and can be used as indicator of the impacts in the environment [116].

To eliminate or decrease heavy metals in mine soils, phytoremediation techniques as well as the combined use of plant species that accumulate heavy metals, soil amendments, and agronomic practices could be a plausible solution [117]. Other kind of heavy metal pollution can result from the continuous stream of polluted sediments, dredged from harbors and water bodies in order to maintain the navigation; it is a common practice, but the fate of these sediments is an issue recognized worldwide. A pilot case study evaluated the application of phytoremediation as sustainable management strategy for the decontamination of polluted dredged marine sediments [118].

In general, and in relation to the remediation process, organic biodegradable sludges have been found to improve the physical, chemical, and biological properties of soils by (1) raising the pH; (2)

increasing the organic matter content; (3) adding essential nutrients for plant growth; (4) increasing the water holding capacity; and (5) decrasing the bioavailability of metals [119,120].

The combination of organic amendments (sewage sludge and domestic waste compost) and mulches (gravel and woodchip) has proved to be a good strategy for restoring degraded soils in semiarid quarrying areas, improving soil physical chemical and microbiological properties, particularly in compost treated soils [121].

Together physical soil degradation, salinization is one of the most serious problems affecting agricultural soils, particularly in arid and semiarid areas, such as those of the Mediterranean basin, where water scarcity has led to the use of low quality irrigation waters. The loss of productivity in saline soils is not only due to the negative effect on soil and plant caused by the excess of soluble salts but also by the scarcity of organic matter, which is aggravated in arid and semiarid areas due to the fact that the adverse climatic conditions (high average annual temperature and scarce but intense rainfall events) existing in these areas, accelerate organic matter mineralization processes. It has been reported [122] that addition of organic amendments, particularly composts, used to maintain or increase agricultural soil fertility can be also a promising way of minimizing the negative effects of soil salinization. Good quality organic amendments are exempt of contaminants, and their high organic matter and nutrient content will contribute to enhance the quality of salinized soils by promoting clay mineral flocculation and soil aggregate formation. Tejada et al. [18] reported that 5 years after the addition of organic wastes (cotton gin crushed compost and poultry manure) to a saline soil under semiarid conditions, the treated soils showed denser vegetal cover (80%) than the non-treated soil (8%) as well as enhanced soil physical, chemical and biological properties.

3. General Benefits Derived from the Use of Organic Amendments for Soil Restoration

Many published studies have demonstrated that organic amendments can help improve soil quality, resulting in soils with greater organic matter content, enhanced agronomic stability and improved soil structure [123,124]. The main functions of organic amendments in soils are as follows: (1) promotion of soil aggregation; (2) provision of plant nutrients; and (3) a reduction in water content loss, in addition to other beneficial functions. Organic amendments are thus applied to improve soil physical, chemical and microbiological properties [38,125]. However, it is essential to carefully characterise and consider all the physical, chemical, and microbiological properties of the potential soil amendments when choosing an organic amendment for restoration purposes (Table 1).

3.1. Effects on Soil Physical and Chemical Properties

Regarding soil physical properties, aggregate stability is one of the most important factors affecting soil quality and fertility. As mentioned previously, organic amendments can contribute to maintain soil physical conditions, including soil structure stability [27]. Accordingly, several publications encourage the use of sewage sludges for soil restoration purposes. It is well known that sludge application improves the quality of soils by improving their physico-chemical properties, increasing soil aggregation, porosity, water holding capacity and hydraulic conductivity and decreasing bulk density [29,126,127]. During the anaerobic digestion of sludges, the more recalcitrant carbon compounds like lignin and humic substances are scarcely degraded. As a result, these compounds are highly reactive and can interact directly with soil surfaces to strengthen the aggregates. The chemical properties of sludge-soil mixtures not only depend on the properties of the soil and sludges and the application rates of the mixtures, but also on their interaction and soil pH [128]. Relatively high rates of sludge application have been found to increase the cation exchange capacity, which helps to retain essential plant nutrients within the rooting zone due to additional cation binding sites. Such responses, however, depend upon the sewage: soil ratio. Sewage sludge addition to soils could therefore also affect the potential availability of heavy metals. Trace metal bioavailability is also dependent on the form of the organic matter, i.e., whether it is soluble (fulvic acid) or insoluble (humic acid). In addition to sewage sludges, composted organic residues such as urban wastes have also demonstrated significant positive effects on soil physical properties, likewise producing increases in stable aggregates, water holding capacity and porosity [21,129]. Organic matter and carbohydrates appear to be the parameters most closely related to the structural [131,132,133] stability of soil aggregates. Organic matter break-down give rise to compounds, particularly carbohydrates that can be linked to soil mineral particles improving soil aggregation. This, in turn, contributes to improving soil resistance to erosion [130]. The increases in these properties, clearly linked to soil fertility and productivity, are closely related to the increase in SOM content produced by the compost [131-133]. Furthermore, the activity of soil microorganisms and their decomposition products also promote soil stability [134].

The application of organic materials can enhance the nutrient status of soils, serving as a source of both macro- and micro-nutrients. Organic amendments can also improve soil physical properties by increasing soil porosity and water retention due to the presence of humic-like substances (poly-condensed macromolecular structure). Furthermore, organic amendments generate progressive plant growth [11,135], and plant inputs promote the development and activity of the microbial biomass in the soil, which in turn, increases soil fertility in the long term [125,136]. Different types of organic amendments have been applied in arid and semiarid environments, including crop residues, pig slurry, farmyard manure, municipal solid waste, olive mill waste and sewage sludges. Despite the potential benefits, however, organic amendments must be used carefully, since they do not always suppose an increase in soil quality. For instance, Tejada et al. [137] reported that the application of fresh beet vinasse worsened the physical and biological properties of the soil due to the sodium ion content of the amendment.

The stability and nature of the amendment used can determine the residence time of the added organic carbon [138,139]. In dryland ecosystems, due to the high potential for carbon sequestration, the stabilisation of SOM is believed to be controlled by both, the quantity of the inputs and their interaction with the soil matrix (i.e., texture) and the quality of the organic amendment [77,140,141]. Fine soil particles are thought to play a critical role in C fixation. Some authors have observed an increase in the carbon fixation in fine particles (clay or silt) after applying organic amendments [141], while others have not found any variation in the organic carbon content of the fine fractions in the long term. Recent studies based on carbon stable-isotope probing have also suggested that clays can protect some added organic compounds in the soil despite their highly labile nature (i.e., ^{13}C-glucose) [88].

3.2. Effects on Soil Biochemical and Microbiological Properties

Measurement of soil enzyme activity has been proposed as a sensitive tool to be used as a potential indicator of soil quality [142], as it integrates the chemical, physical and biological characteristics of the soil. Since mature composts consists of about 30–50% organic C [143], the addition of compost to soil—even at small amounts—has a considerable effect on SOM content, which typically ranges from 0.1 to 5%, depending on land use, vegetation and contamination [99]. The addition of organic matter to the soil also leads to a significant shift in microbial activity due to changes in soil properties and substrate availability. An increase in the activity of certain soil enzymes, such as β-glucosidase indicates energy release for microorganisms, as an attribute of the type of organic matter added to the soil. This agrees with other studies demonstrating that composts from wastes stimulates microbial activity in soils, increasing organic matter mineralisation and thus supporting microorganism growth and activation [34,129,144]. The mechanism that drives the increase in microbial activity could be an apparent priming effect [145,146], by which fresh organic matter inputs can activate soil microorganisms, promoting the degradation of SOM as a result of activated co-metabolism [147]. It is assumed that the intrinsic microbial activity of the compost surrenders to the activity of the original population in the soil with minimal impact on the soil microbial community [148]. Any changes occurring in soil microbial characteristics are thought to be due essentially to the input of a compost matrix rich in organic matter and only marginally to the input of compost-borne microorganisms [11,148]. In contrast, other studies have shown that the incorporation of external organic matter to the soil matrix can modify its microbial community by adding a considerable amount of compost-bond microorganisms (bacteria and fungi), which may result in competition and/or antagonism with the existing soil microorganisms for resources [149]. This scenario can lead to a decrease in soil microbial biomass, although it does not necessarily have to affect the overall soil microbial activity. In some cases, involving sewage sludge additions, negative effects have been observed in soil enzymatic activities due to metals present in the sludge [150], depending on the sludge origin. Generally, however, sewage sludges have been found to increase soil microbial activity, soil respiration and soil enzyme activity. Pascual et al. [151], for example, observed a positive effect on hydrolase enzyme activities and a significant increase in soil microbial biomass 10 years after applying municipal solid waste (MSW) to an abandoned agricultural soil. This suggests that the reactivation of the biochemical cycles of N (urease and protease-BAA activity), P (phosphatase activity) and C (β-glucosidase activity) caused by the added organic waste, and the consequent improvement of soil fertility, persisted 10 years after the organic amendment. These benefits were linked to a re-established vegetation cover, which contributed to the observed long term effects. Since approximately half of the organic matter added as MSW was mineralised in the first year, these authors [151] attributed the higher organic C content observed in the restored soils compared with the control after 10 years, to the presence of a well-established plant cover, which will continuously provide C to the soil throughout root exudates and plant remains. Organic amendments not only increase the SOM content, but also lead to the development of a natural vegetation cover capable of maintaining the natural process of nutrient cycling in soils.

To give another example, Carlson et al. [50] conducted a restoration assay in a degraded industrial soil using great doses of different types of organic amendments: vegetative yard compost, biosolids from sewage sludge, a mixture of biosolid and biochar, and a water treatment residue. They found that, at the biochemical level, the addition of biosolids—alone or mixed with biochar—led to increases in the enzyme activity in the receiving soil in comparison to the control soil even 3 years after application. At the microbiological level, the addition of biosolids increased the presence of fungi in the soil and reduced the quantity of some stress biomarkers in the degraded soil, promoting the recuperation process. Fungal populations still dominated the soil 3 years after the addition, highlighting their great ability for degrading the more recalcitrant compounds. Given these results, the authors suggested repeated biosolid applications at least every 3 years, with the aim of achieving long term effects on the soil enzyme activities.

According to Aguacil et al. [152], the application of organic amendments (urban refuse) can have a positive effect on the proliferation of natural arbuscular mycorrhizal (AM) fungi in crop systems. The stimulatory effects of the addition of organic matter on the development of AM fungi could be related to an improvement in the extensive network of AM fungal mycelium in the soil. These authors concluded that the addition of different doses of urban refuse improved a wide spectrum of soil properties related with microbial activity when measured 19 years later, and the increase was proportional to the applied dose. The AM fungi community was also more diverse after applying the amendment. Subsequently, Hernández et al. [21] also observed increases in the organic C fraction in soils amended with composted urban waste, even 5 years after application. The soil nutrient and humic substance contents were greater in the amended soils than in the control, and the greater applied dose (3%) produced greater increases than the smaller dose (1%). As a result, soils receiving the greatest dose of this compost also showed the highest values of basal respiration, dehydrogenase activity and β-glucosidase and phosphatase activities, as well as a greater microbial biomass. It has thus been demonstrated that the application of large amounts of organic amendments is an appropriate strategy for repairing the microbial and biochemical status of degraded soils.

Sequencing techniques have started to provide a deeper understanding of the composition of soil microbial communities, enzyme activities and community-level physiological profiles [153,154]; These techniques are valuable tools for assessing the potential ability of soil microbial communities to metabolise a range of substrates [155]. Beyond this, new advances in genomic and proteomic approaches are making it possible to establish links between soil microbial community structure and function, improving our understanding of the processes that mediate the generation and mineralisation of SOM, especially in degraded soils, before adding organic matter. Bastida et al. [28] studied the long-term responses of the microbial community of a degraded and abandoned soil to fresh and composted sewage sludge addition. They found that the type of organic amendment did not affect the internal metabolic processes or lifestyles of the dominant microbial groups (Proteobacteria), suggesting that the differences between restored and non-restored soils are mainly controlled by extracellular enzymes and proteins linked to microbial biomass. The Proteobacteria community, a dominant microbial group in arid soils in general, increased significantly in the restored soils, as other authors have observed [28,156,157]. According to Chaudhry et al. [157] in long term restoration experiments, organic compost amendments activate diverse groups of microorganisms to a greater extent than conventionally-used synthetic chemical fertilisers, suggesting that soil quality improvements are due to the reactivation of the microbial metabolic routes.

Organic amendments favour the development of a spontaneous vegetal cover when added to degraded soils. The relationship between plant cover and microbial community composition has been explored extensively and it has been reported that the presence of plant cover shapes the structure of microbial communities in soils in the Negev Desert [158], the Colorado Plateau region [159], South-east Spain [160] and central Chile. Furthermore, Angel et al. [161] studied the diversity and community composition of archaea and bacteria along a climate gradient in Israel and found differences among different climate sites due to the precipitation gradient and vegetation cover.

Table 1. Principal effects of the organic amendments typically used for restoration purposes.

Properties	Effect	References
Physical properties		
pH	Decrease	[11,172]
pH	Increase	[66,71]
Soil aggregate stability	Increase	[29,126,127]
Bulk density	Decrease	[29,126,127]
Water holding capacity	Increase	[21,29,72,126,127]
Porosity	Increase	[21,29,126,127]
Erosion	Decrease	[126]
Humic content	Increase	[21,190]
Chemical properties		
TOC	Increase	[26,71,99, 143,177]
EC	Increase	[21,72,127]
N and P	Increase	[27,31,32, 71,127,177]
Heavy metals	Increase	[174,176,190,191]
Biochemical and microbiological properties		
Microbial activity	Increase	[21,26,50,59,129,148,151]
Basal respiration	Increase	[21,151,177]
Microbial biomass	Increase	[21,59,152]
Pathogenic level	Increase	[127,190]

Several groups of authors have explored the composition and structure of the soil bacterial community in the arid area of Atacama (Chile). For instance, Neilson et al. [162] studied the bacterial diversity in unvegetated soils from the hyperarid margin of the Atacama Desert and found a high abundance of novel Actinobacteria and Chloroflexi, and greater community diversity and different community structure than that found for other authors [163,164] in also devegetated hyperarid regions. These authors [162] attributed the enhanced bacterial diversity found at the hyperarid margin to exposure to past vegetation history. Connon et al. [163] also found a predominance of Actinobacteria whereas Drees et al. [164] found a predominance of Gemmatimonadetes and Planctomycetes in the hyperarid devegetated areas of Atacama.

Similar patterns have been noted in other arid and semiarid areas of the planet, indicating a common eco-biogeography of the bacterial communities. For instance, Bastida et al. [88] found that Actinobacteria was also dominant in arid soils from south-east Spain and that it relative abundance diminished in restored amended soils; some minor bacterial groups (Gemmatimonadetes and Planctomycetes) were also less abundant in a control soil than in a restored soil. Despite their low abundance, the ability of the Gemmatimonadetes and Planctomycetes to trigger in degraded areas must be explored more deeply from a functional point of view.

4. Are the Quantity and Quality of Organic Amendments Factors of Paramount Importance in Soil Restoration?

The abandonment of Mediterranean soils after intensive agricultural practices results in a loss of soil quality, and the longer the soils are left abandoned, the more degraded they become [151]. The main reasons for this decline are probably a combination of the low levels of organic matter, nutrients and microbial activity in the soil. Adding organic wastes to abandoned and degraded soils can be a good strategy for preserving and improving soil quality for future use. As we mentioned before, organic amendments not only increase the organic matter in the soil, but they also stimulate the development of natural vegetation capable of maintaining significant microbial biomass in the soil and providing an almost steady supply of nutrients via plant inputs into the soil (Table 2). The relationship between organic amendments and organic C retention in soils has been studied by several different authors, who have reached contrasting conclusions regarding the adequate quality and quantity of the different types of organic matter applied to the soil. For instance, Drees et al. [165] showed that inputs of fresh organic matter accelerated the decomposition of soil C and induced a negative C balance, increasing CO_2 emissions from the soil into the atmosphere. In relation to the quality of the amendment, Tejada et al. [60] observed a positive impact in soils amended with composted organic residues rather than with fresh organic residues. Fresh organic amendments, such as beet vinasse, cattle manure and untreated sewage sludge, usually decrease soil structural stability, reducing soil porosity and affecting the physical and biological properties of the soil due to the presence of sodium ions, among others. This suggests that not all kinds of residues are adequate for direct application in soils. Plaza et al. [37] indicated that pig slurry was not appropriate for use on agricultural soils because it increased the soil microbial population due to the addition of an easy mineralisable C source, which did not contribute to the formation of a stable organic C pool in the soil. Furthermore, in N-rich environments provided by the addition of animal manures and slurries, the C content is scarce and the soil often responds to this perturbation with further increases in the mineralisation of indigenous SOM, resulting in a net loss of C and N. In contrast, composted residues hasten increases in SOM [142]. During composting, the biodegradable organic compounds are mineralised, whereas some of the remaining organic materials become precursors of humic substances [166]. During the decay and transformation of biomolecules, humic acids are formed by secondary biotic synthesis reactions or re-synthesis [167], so the humic substances are considered as the final product of organic matter stabilisation. As a result, the humic substances play an essential role in biochemical soil reactions, such as the reduction, oxidation, sorption and complexation of pollutants and C sequestration [168,169]. The different type of raw materials used for composting will determine the generation of different humic substances depending on their chemical composition [166,170,171]. In the environment, chemical components of humic acids, such as polyketides and humins, are extremely resistant to biodegradation, with a half-decay time of thousands of years [167,172]. These components are thus part of the more stable fraction of SOM. According to Lynch et al. [173], 75–95% of the C applied through compost remained in the soil one year after the compost was applied, increasing the recalcitrance of the organic matter with prolonged storage in the non-mineral soil fractions.

Table 2. Compilation of some examples of organic amendments used in the restoration of degraded and abandoned agricultural soils.

Reference	Organic material	Application rate	Soil type	Period of time	Reported benefits
[151]	Municipal solid waste	6.5 and 26 kg m^{-2}	Abandoned agricultural soil (Spain)	Long term (20 years)	Reactivation of soil biochemical functions and increase in soil fertility
[59]	Municipal solid waste compost (MSW) and cow manure (MA)	MSW at 20 and 80 t ha^{-1} and MA at 20 t ha^{-1}	Agricultural soil (Spain)	Long term (9 years)	MSW compost can improve soil quality, increasing the organic matter content and improve soil biological and biochemical properties
[125]	Fresh and composed urban waste	25–30 kg m^{-2}	Abandoned agricultural soil (Spain)	Short term (1 year)	Increases in organic matter and microbial biomass, the maintenance of the soil's biochemical cycles and the establishment of a plant cover
[174]	Composted municipal solid waste (MSW)	40, 80 and 120 Mg ha^{-1} of MSW	Calcareous soil (Spain)	Short term (5 years)	MSW application has a positive effect on the soil chemical properties and promotes the growth of native vegetation without causing environmental damage
[60]	Beet vinasse, green manure and a composted mixture of both residues	Equivalence of 10 t organic matter ha^{-1}	Restoration of a Xelloric Calciorthid soil (Spain)	Short term (4 years)	Beet vinasse had a detrimental effect on soil properties while green manure and the composted mixture had positive effects on soil physical and biological properties
[11]	Municipal solid waste	65, 130, 195 and 260 t ha^{-1}	Semiarid abandoned soil (Spain)	Long term (17 years)	Improvement in the soil biochemical properties and changes in the soil microbial community
[152]	Organic urban refuse	6.5, 13.0, 19.5 and 26.0 kg m^{-2}	Mediterranean semiarid soil (Spain)	Long term (19 years)	Improvement in the soil biochemical and microbiological properties in relation to the applied dose
[64]	Hydrolysates organic biofertilisers or biostimulants	4.7 t organic matter ha^{-1}	Eroded soil (Spain)	Short term (3 years)	Positive effect on soil biological properties, and favourable to vegetal establishment
[177]	Composted sewage sludge	30, 60 and 90 Mg ha^{-1}	Abandoned agricultural soil (Spain)	Short term (3 years)	Increases in chemical and biological soil properties at higher doses
[179]	Composted dry organic green waste	7 Kg m^{-2} (1.42 kg C m^{-2}, and 129 g N m^{-2})	Grassland soils (California, US)	Short term (3 years)	A single application of compost increases soil C and N storage in labile and physically protected pools over relatively short time periods, contributing to climate change mitigation

Continued on next page

[28]	Composted and anaerobic digested sewage sludge	12 kg m^{-2}	Arid-degraded soil (Spain)	Long term (10 years)	The long-term impact of organic restoration affects soil microbial community function and structure, and it depends on the material added to the soil
[50]	Vegetative compost (VC) and biosolids (BS)	137 mg ha^{-1} (VC); 202 and 403 mg ha^{-1}(BS)	Degraded soil (Illinois, US)	Short term (3 years)	Stimulates fungal populations and soil enzyme activities
[26]	Pelletized plant, animal and sewage sludge compost (PEL); Municipal solid waste compost (MSW); Sheep manure compost (SMC)	3700 of PEL, 4075 of MSW, and 4630 kg ha^{-1} of SMC (fresh weights)	Vineyard soil (Spain)	Long term (13 years)	Continuous long-term application of organic amendments positively affects soil quality, increasing microbial activity, C storage and denitrification potential
[223]	Urban municipal solid waste compost (MSW) and alfalfa residue (AR)	10 and 30 Mg ha^{-1} (MSW and AR)	Semiarid soil (Kerman, Iran)	Short term (2 years)	Higher respiration and decomposability in the MSW-treated soils resulted in greater formation of water stable aggregates and an increase in the macro-pore fraction, but reduced levels of SOC more than in AR soils.
[213]	NPK + straw (NPK + s), and NPK + manure (NPK + m)	37% NPK + s and 32% NPK + m (more N input than for NPK alone).	Paddy soils (China)	Long term experiment s	Manure can increase the rice yield and soil C sequestration. Applying both chemical and organic fertilisers (NPK + m) leads to a longer duration of soil C sequestration than a chemical fertiliser alone.

Regarding the effects of organic amendments on soil biochemical reactions, Carlson et al. [50] found that the greatest impact on soil enzyme activities occurred within the first year after amending. The treatment effects were transitory, and after 3 years, certain enzyme activities were either equal to or nearly equal to the control levels. These authors suggested that repeated applications—at least every 3 years—may be needed for achieving long term effects on soil enzyme activities. However, the initial increase in activity generated by organic amendments may be sufficient to restore a natural vegetative cover in the short term. This study also provides evidence that composts made from biosolids or treated sewage sludge produce more significant and longer-lasting increases in fungal groups in the soil than urban waste, probably due to the unique ability of the former to degrade the more recalcitrant organic compounds, which is encouraged by adding large rates. Both the quality and the quantity of the organic amendments added thus influence the effectiveness of the restoration process.

Many authors have affirmed that a single application of a high dose of organic matter is usually enough to recuperate the plant cover in degraded soils [50,86,174] by maintaining high organic C levels for a long period of time. Normally, a period of five years should be enough to observe a natural restoration process when a plant cover develops [21]. According to Henández et al. [21], adding large amounts of compost in a sole application leads to greater improvements in the physical, chemical and microbiological properties of the soil and to a greater increase in the pool of organic C in degraded soils in semiarid zones. Due to their low natural organic matter content, these soils are able to receive large amounts of exogenous organic C, which remains in part fixed in the soil in a stable manner as humic acids. Other authors [175,176] have suggested to use an application frequency of once every other year after the initial addition of an organic amendment (compost in both cases), because the N release from compost mainly occurs in the first two years, yet only 30–35% of total N is released during the first year. The residual effect of cumulative applications leads to deferred greater N availability and yields, indicating physical protection of this nutrient within macroaggregates [27]. Normally, the applied dose and the time elapsed since the amendments are closely related. In short-term experiments, greater application rates cause a greater response in soil biochemical and microbiological parameters, whereas the physical properties of the soil may not have changed as much as the biological properties, because the latter properties are more sensitive indicators. A study conducted by Fernández-Getino et al. [177] showed that applying large doses (60 and 90 Mg ha^{-1}) of biosolids to the soil significantly increased several chemical and biological soil properties, such as organic C content, humified C fractions, water soluble C, total N, basal respiration, and potential N mineralisation, without impairing the soil physical properties. Fabrizio et al. [178] and Ryals and Silver [179] found that large doses of organic amendments increased the amount of C sequestered in the soil, with little impact on the microbial community [180]. Bastida et al. [136] observed similar effects in a long term soil restoration assay (25 years) using domestic solid wastes. These authors observed an increase in the soil nutrient content, although the treated soil did not support a more diverse microbial community than the control soil. This study also found that the application of large doses of organic wastes (195 Mg ha^{-1}) indirectly modified the structure of the bacterial and fungal soil communities and that these effects were mainly mediated by the development of natural vegetation and changes in soil pH and the organic C and N concentrations in the soil. Small doses, however, did not modify such community structure, but they did foster microbial activity to the same extent as in plots amended with large doses.

5. Are These Effects Maintained in the Long Term?

Because of the long period of time required for a degraded soil to reach a new equilibrium, the effect of organic amendments on the SOM should be studied in long term field experiments [27] rather than in short term assays. Macias and Camps-Arbestain [181] found that, in general, the addition of a great amount of organic matter makes a larger fraction of the SOM susceptible to oxidation and microbial decomposition. However, according to the literature, the degradation rate depends on the quality of the organic matter [182], its distribution [183] and the priming effect caused in the microbial community [146]. In a long term experiment conducted by García-Gil et al. [59], multiple additions of municipal solid waste compost at rates of 20 and 80 Mg ha^{-1} increased microbial biomass C, and this increase persisted even 8 years after application. Soil basal respiration, a parameter used to monitor microbial activity, has also been found to increase and persist 8 years after compost application [53].

The long-term impact of anaerobic digestates on soil properties remains an unexplored field of research. A 4-year field trial conducted by Odlare et al. [184] in eastern Sweden showed that soil chemical properties hardly change in the short term when soil is amended with organic waste, including digestates. However, relative to other treatments (pig manure, cow manure, compost, inorganic fertiliser), the soils treated with liquid digestates from household wastes displayed the greatest microbial biomass, N mineralisation rate and ammonia oxidation potential. This suggests that liquid digestates affect the soil chemical and microbiological properties in the short term, whereas their effects are not as significant in the long term, as we have mentioned before. Microbial biomass and potentially mineralisable N have been commonly suggested as biological and chemical indicators of soil quality in restoration initiatives, since both parameters are sensitive to organic amendments [185].

In the short and long term, both the nature and quality of the organic amendment used therefore affect the microbial soil response. Calleja-Cervantes et al. [26] found that several composted organic residues did not affected the soil bacterial community in the short term (15 days after application). Furthermore, the effects did not vary according to the type of compost, and all treated soils responded uniformly to environmental changes, without suffering too much damage to the microbial soil community structure and composition. In contrast, Ge et al. [186] reported that the application of manures from farming caused pronounced changes in the composition of the bacterial community. Undoubtedly, this difference is due to the type of organic amendment used. Composted residues have gone through a process of chemical and microbiological stabilisation, and the resulting product is a safe, high quality organic amendment. The application of fresh organic amendments produces modifications in the chemical and microbiological soil properties in a shorter period of time. However, such fresh amendments are less efficient in fomenting the long term restoration of SOM.

The benefits of long-term soil restoration also include the effects of the plant cover in the soil. Plant cover is a natural source of organic amendments, providing root exudates that may act as substrates for enzymatic activities [11]. In addition, plant inputs contribute in the long term to the pool of humic substances that could be linked to enzymes. Some studies using organic amendments have concluded that the greatest doses are most effective in sustaining significant differences in organic C content compared to the control soil [21], whereas others maintain plant cover but do not show a higher organic C level. In the case of a sole addition, the effects diminish over time, but if a plant cover develops, it contributes to C inputs in the soil. In the case of dryland agroecosystems, such as those found in the Mediterranean region, the application of organic amendments must be accompanied with conservational management practices in order to maintain the C reserve in the soils [7].

6. Environmental Risks of Soil Restoration Strategies

Sewage sludges are among the most widely used organic amendments in soil restoration, although it remains controversial due to the possible transference of potentially toxic elements to the soil [187-190]. These elements include metals, pathogens and organic pollutants, which can sometimes reach the soil if they are not properly eliminated in the sanitisation process. This can be a serious problem in agricultural soils when sewage sludges are used for long periods of time [29,191]. The use of animal manures also represents a risk of pathogen contamination [192]. Bacteria such as

Salmonella, *E. coli*, *Yersinia*, *Campylobacter* and the protozoa *Giardia* and *Cryptosporidium* are the most prevalent pathogenic microorganisms found in manures [193,194]. The risk of pathogens embedded in manures can be mitigated, however, through integrated or post-sanitation configuration of the anaerobic digestion process [195,196]. Despite hygienisation, pathogenic parasite eggs, bacteria and fungi have been found to persist in many biogas plants [197,198]. Nevertheless, heavy metals and other harmful substances are regulated in Europe by the Council Directive on the protection of the environment, particularly in agricultural soils subjected to sewage sludge treatments [199]. The risk of contamination is not such a disadvantage in the restoration of degraded and abandoned soils, however, in which the permitted level of pollutants is not as strict as it is in the case of agricultural soils.

There are also other environmental risks derived from the use of organic amendments in soil restoration such water run-off contamination, when the amendment is left in surface without incorporation into the soil, or soil salinization [200,201]. Organic amendments, particularly composts, can contain great amounts of salts becoming a potential risk when added to the soil due the known detrimental effect that salinity has on soil structure and plant growth [202,203]. In addition, under some particular irrigation conditions salts can be lixiviated from the amendment increasing the risk of groundwater contamination by nitrates, P compounds or heavy metals [204]. The salinisation risk depends in part on the quality of the soil and subsoil, especially in terms of pH and texture. Acidic soils, for example, have a higher potential to solubilise salts. Sewage sludge compost could also favour the solubility of metals because its pH is slightly acidic. According to Diacono and Montemurro [27], environmental problems associated with organic amendments are closely related to the application of immature compost and organic materials that have not been sufficiently stabilised by composting or anaerobic digestion. Such problems include increases in ammonia volatilisation, decreases in the soil oxygen concentration, the production of phytotoxic compounds, and the immobilisation of soil mineral N. According to the literature reviewed on this topic, however, there is plenty of evidence supporting the capability of stabilised organic amendments to improve the physical, biochemical and microbiological properties of the soil.

7. The Future: Why Should We Protect and Restore Our Soils?

Soil is one of the most complex biomaterials on earth [205], and it is a key component of the terrestrial ecosystem operating at the interface of the lithosphere, biosphere, hydrosphere and atmosphere. While climate, food, water, biodiversity and energy have received much attention in strategic international environmental publications, this is less the case with soil science. According to Dominati et al. [206], it is therefore essential to emphasise the role soils play in providing ecosystem services, given that soils are an important part of ecosystem functions (Table 3). Several authors [207-209] have discussed the pressing need to include soils in ecosystem service frameworks and policy decision-making. Recently, following the UN-Sustainable Development Goals (SDGs) proposed by Bouma [210], soil science has been included in the ecosystem services net. Soil ecosystem services depend on soil properties and their interactions and are mostly influenced by soil use and management [4]. Landslides, erosion and decreases in soil C and biodiversity lead to soil degradation, which is a serious global challenge for food security and ecosystem sustainability [211,212]. The contribution of soils to human welfare beyond food production must also be recognised [208], and this can be accomplished by incorporating soils into ecosystem service frameworks and demonstrating the multitude of functions soils provide to our society [206].

Table 3. Ecosystem services according to Dominati et al. [206].

Provisioning services
Provision of food, wood and fibre
Provision of raw materials
Provision of support for human infrastructures and animals
Regulating services
Flood mitigation
Filtering of nutrients and contaminants
C storage and greenhouse gas regulation
Detoxification and the recycling of wastes
Regulation of pests and disease populations
Cultural services
Recreation
Aesthetics
Heritage values
Cultural identity

The emerging term "domesticated soil" is used to designate a soil managed in a way that improves its efficiency in capturing and storing atmospheric CO_2 [213]. Using improved management practices on cultivated soils can sequester organic C at a rate of 0.36 Gt year^{-1} and increase N use efficiency by 32–57% [214].

C sequestration is among the most important soil functions. More precisely, C sequestration implies the fixation of atmospheric CO_2 via plant photosynthesis and its storage as part of the SOM. On the other hand, the soil C pool can be a source and sink for the atmospheric CO_2, depending on the land use and management practice [134]. Terrestrial soils contain reserves of organic C estimated at between 1500 and 1700 Pg [215]. SOM is an often recalcitrant complex that is both synthesised and degraded by microbial enzyme activities. The balance between these two competing processes determines how much C is sequestered, contributing to the following indicators of soil quality: soil aggregate structure and stability [216]; plant nutrient availability; water retention and soil management [217]; microbial diversity and activity; and a host of enzymatic properties that determine soil fertility and plant productivity [218,219]. By using organic amendments, we are therefore able to alter the outcomes of global warming by increasing the organic C stored in the soil [181]. It is necessary, however, to take into account soil microbial responses, including soil enzyme activities, which may affect recalcitrant humic matter [220]. It is also important to consider the impact of manipulated C sequestration, specifically in the form of biochar additions, on soil microbial and enzymatic properties [221], contributing to C storage in the soil. A study conducted by Montiel-Rozas et al. [222] to evaluate C sequestration in soils restored by applying organic amendments (leonardite and biosolid compost) revealed that both amendments promoted soil C storage while improved soil characteristics. This positive effect on C storage depended on the application rate and on the characteristics of the organic amendment being greater for the more aromatic material (leonardite).

8. Conclusions

Soil is a finite natural resource. The increasing degradation of soil caused by population pressures, environmental conditions and inadequate governance over this valuable resource, has become a worrying reality. In addition, the sustainable and productive use of the world soil resources should therefore be recognized as a primary goal in the future. But this valuable resource is threatened and urgent actions have to be implemented in order to assure the necessary soil restoration and to maintain edaphic fertility for future generations. All of this is particularly urgent in soils under arid and semiarid climate.

In this scenario, some important points to be taken into consideration are the following:

(1) Soil degradation processes put at risk soil conservation and protection, constituting a serious problem in arid and semiarid environments. Climate change could increase this risk. In this sense, the loss of organic matter is one of the main threats for soil degradation, pointing to the exogenous organic matter (that can be added to the soil as amendment such as organic wastes) as an invaluable source of organic matter, contributing not only to soil restoration but also to fixing C in such soil. So, organic wastes with an adequate quality, can be a good source of organic matter for soils, and for this reason the addition of such organic wastes can be a good strategy for degraded soil restoration.

(2) In order to obtain the best results for soil restoration when organic wastes are used, some aspects should be considered; for example, in order to reduce the loss of the C proceeding from the organic amendment by mineralization, it could be necessary in some cases to stabilize such C by mean of mechanisms that allow elongating its life in the soil. In addition, to stablish the quality of organic amendments, the application doses for the organic amendments (for instance, to determine if it is possible a unique organic amendments addition to degraded soils in arid and semiarid areas), the adequate management of such organic amendments, will be important for the success in soil restoration. In this sense, several parameters which can help to monitor organic waste quality, and soil restoration are also necessary.

(3) When organic amendments are recycled in the soil, some soil properties (physical, chemical and biological) can change. Organic amendments are a “live organic material”, and they can induce changes in the soil biota. Soil organisms provide numerous and essential services. We need progresses in the knowledge of soil community microbial compositions in soils amended with organic wastes; the cycles of key nutritional element such as C, N, P and S are closely related with specific microbial populations and for this reason with soil fertility and quality. Soil biodiversity is difficult to characterize but there are new techniques which have allowed exploring soil in a way that was not previously possible; techniques (PFLAs, -omics as genomic and proteomic, together with other techniques such as soil respiration or soil enzyme activities) incorporated to soil science study, particularly to the study of soil rehabilitation when organic amendments are used, should be

standardized. Biodiversity in soils restored with organic amendments can help to understand soil sustainability, and it could be the key for soil production in the future.

As a general conclusion, it can be indicated that the recycling in the soil of organic amendments, normally based on organic wastes, never must be a dumping but a consistent application. It is urgent to legislate to protect the soil against possible external aggressions, such as the use of organic amendments (organic wastes) of very poor quality; however, when soils can accept exogenous sources of organic matter such as amendments based on good quality organic wastes, and this addition is done in a controlled manner, this strategy can be very useful to improve the fertility of such soils, avoiding degradative processes in them.

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Conflicts of interest

Authors inform that there is not any conflict of interest.

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