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The role of organic amendments in drylands restoration

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Abstract

Dryland areas are being seriously affected by degradation processes. The use of organic amendments in ecosystem restoration is an effective technique for accelerating soil regeneration processes in degraded drylands. This recovery is a result of the rapid increment of organic matter and clay contents in the soil in the short term. In the long-term, soil structure becomes more stable and water holding capacity, permeability and infiltration are improved, whereas surface runoff and erosion are reduced. This review evaluates the role of organic amendments as an effective strategy in dryland restoration, highlighting the effects of different amendment types, doses and application rates. The major points of our analysis are: (a) the effects of the amendment on soil properties largely depends on the amendment origin; (b) amendments need to be applied at the minimum effective doses; (c) the form of application most extensively applied is on the soil surface ("on-top"); and (d) the stability and maturity of amendments can make the difference between success and failure.

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Soil organic carbon, Land degradation, Desertification, Soil fertility, Organic residues.

Introduction

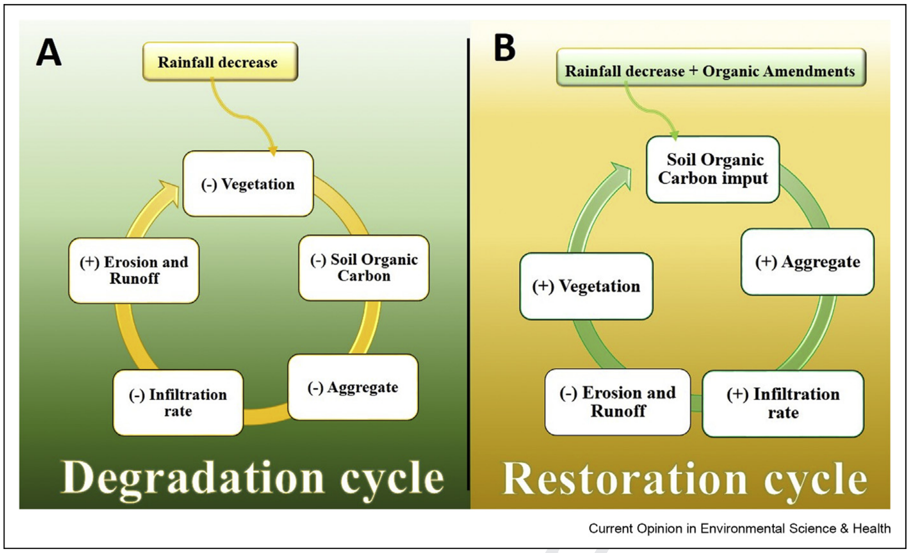
Drylands, defined as regions with an index of aridity ranging between 0.05 and 0.65 [1,2], cover approximately 5.2 billion ha, which represent 40% of the global land surface [1,2]. Most of these areas are seriously affected by global change processes [3]. This is leading to desertification scenarios where dryland ecosystems are losing their capability to produce ecosystem services due, among other causes, to a reduction in the soil water available for plants [3–6].

There is a large consensus on the effects of future climate in dryland systems, that will be characterized by: (i) higher temperatures, (ii) an increase in the degree of aridity, and (iii) shifts in the seasonal rainfall regimes and a greater frequency of extreme events [7–9]. These changes will affect the size, frequency, intensity, and timing of rainfall events, which largely determine the structure and functioning of dryland ecosystems worldwide [10,11]. To unravel this complexity, we should focus on understanding how biotic attributes interact with abiotic factors to ultimately drive ecosystem functioning [5]. In the near future, a decrease in organic inputs into the soil by decreased litter cover, is expected in dryland ecosystems [5,12]. As a result, soil organic carbon contents will decrease, generating a reduction of soil stability and size of the aggregates [14]. In the long-term, lower water holding capacity, permeability and higher probability of crust formation are forecasted and, thus, a dramatic decrease in infiltration rates [14–16]. Finally, due to the absence of available water in the soil profile, vegetation will not be able to re-establish resulting in high rates of overland flow and sediment yield [15,16]. Consequently, the seedbank and nutrients contents will diminish, and a second cycle of decreasing soil organic carbon content will commence [13,16] (Fig. 1A). This positive feedback may not be spontaneously reversible in drylands and thus, restoration may be necessary to restore natural conditions and vegetation cover [17,18].

Restoring drylands areas

According to the Society of Ecological Restoration [19], "ecological restoration" is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. Ecological restoration is predominantly focused on the recovery of functional plant communities as they have a controlling influence on energy flows, hydrology, soil stability, habitat quality and network dynamics [17,18,20]. Thus, numerous studies have assessed the use of organic amendments as a restoration technique for better vegetation establishment and increased of soil fertility [21–25]. This beneficial effect is a result of the rapid increase in soil organic matter in the short term. In the long-term, soil structure become more stable and water holding

Figure 1



Interrelationship between the eco-geomorphological elements in drylands systems in response to Global Change. Degradation and restoration cycle using organic amendments.

capacity, permeability and infiltration are improved, while surface runoff and erosion are reduced [14,26,27]; consequently, vegetation growth and development are enhanced (Fig. 1B) [28–30].

Organic amendments. Past and present

Historically, the application of different types of manure has been a traditional agricultural practice in drylands systems [31]. However, due to the Green Revolution in the second part of the 20th century, this practice was replaced by new scenarios of massive production using farming, fertilizers and pesticides to expand monoculture plantations [32]. Under the new paradigm of the European Circular Economy Strategy, all European Union member countries must transition to a green economy where resources are environmentally conserved, and generated waste is reused [33,34]. There are social movements emerging and demanding a return to traditional fertilization practices to safeguard cultural heritage and environmental resources [31]. However, the current framework is very different to than past conditions due to the high division in agricultural sectors and livestock practices [33]. As a result, different alternatives to traditional manure are being explored for use as organic amendments, in order to enhance soils and vegetation without damaging ecosystems health.

Amendments, types and selection criteria

An "organic amendment" is any organic material, including compost, animal manures, crop residue or synthetic soil conditioners that is incorporated into the soil or applied on the surface to enhance plant growth [35]. The term "organic amendments" include diverse techniques ranging from mulch to organic waste and biofertilizers [35,37]. The common characteristic of soil organic amendments is that they contain organic matter to a certain concentration. However, depending on the amendment origin, the proportion and composition of the organic matter may vary and thus, the effects of their decomposition in the soil [26,27]. Although there are many types of organic residues, only a few have an extended practical use [36,37]. The most common are summarized as follows: i) "mulch", defined as an organic or inorganic layer applied to the topsoil; ii) "biofertilization techniques", defined as the extra addition to the soil of microorganisms or enzymes; iii) "sewage sludge", organic by-products of human activity that can be added to soil; iv) "manures of animal origin", most commonly used varieties are gallinaceous, earthworms, porcine, bovine or sheep origin; and v) "compost", any organic product obtained as result of a composting process. Notably, in some studies, the combinations of different types of amendments have demonstrated better results than their individual application [38].

Regardless of the selected type of amendment, the stability and maturity of the organic material are important factors to consider [36,39]. "Stability" is related to the rate of organic matter decomposition and "maturity" refers to decomposition of potentially phytotoxic organic substances [40]. Hence, when a restoration plan is designed, the most critical step is to decide whether to intervene or not, and in the case of carrying out some action, what stability and maturity of amendment is more appropriate [27]. Application of unstable or immature organic amendments may induce adverse effects on soil properties [27]. These negative effects include increased mineralization rate of native soil organic carbon, alteration of salinity and acidity, microbial immobilization of available nitrogen, and addition of phytotoxins and animal pathogens into soil and water [36,38,39]. Hueso-Gonzalez et al. [26] showed that the lack of previous composting in two types of organic mulch did not affect soil organic carbon 4-years after amendment addition. Raw biosolids have proved to increase nitrogen contents very rapidly, giving a burst of fertility that promotes annual weed species, which may dominate the vegetation and reduce biodiversity [41]. Méndez et al. [42] reported that plants were adversely affected by salinity and acidity after addition of unstable organic material.

Amendments, doses and application methods

There are multiple opinions and approaches regarding the proper application doses of soil amendments. Several studies have shown that amendments should always be applied at the minimum effective doses, without posing a risk of contamination to the restored ecosystem [26,38]. Therefore, the rate of the modification depends on the final objective and the previous soil condition [36]. According to the theory of carbon saturation, lower soil organic carbon contents result in higher carbon stabilization efficiency [43]. Likewise, higher application rates positively influence the use of organic amendments, as long as the nutrient loss of the soil system is minimized [44].

In regards to the form of amendments application to the soil, the most extensive method of amendments is application on the soil surface (“on top”). This is because the overturning and mixture of amendments and soils would incur greater economic costs and cause greater disturbance by forcing the mixture of the horizons [25].

Systemic benefits derivate of the use of organic amendments

Table 1 shows a bibliographical compilation of diverse studies conducted in dryland conditions. In general terms, the addition of organic waste to soils is based on the principle that the amendments increase the content of organic matter due to its decomposition [23–25]. However, this process does not follow a regular pattern, but instead depends on time and climate [45]. Variation in organic carbon content usually occurs gradually and several months after the amendment application [46,47]. It has been demonstrated that soil composting from organic waste represents a highly effective strategy to fight the depletion of organic carbon suffered by agricultural soils in dryland systems [47], although in some cases, the temporal range of change is higher and depends on the annual rainfall depth [48–50]. Jordán et al. [46] also evidenced the rapid effects of the applied organic amendment on soil organic carbon with lower rates. These authors showed that mineralization rates of

Table 1

Bibliographic compilation on the positive effects provided by the use of organic amendments in dryland regions.

Effect on soil properties	Reference number
Soil organic carbon increase	[23–26,31,45–47,52,53]
Bulk density decrease	[59–61]
Soil porosity increase	[27,47,62]
Favours soil aggregation	[26,48,62–65]
pH modification	[26,36–38,40]
EC modification	[26,45,48,52]
Soil nutrient increase	[54–57,63,65]
Soil microbiota increase	[49,55,58,62]
Calcium carbonate decrease	52
Effect on hydrology	
Overland flow decrease	[27,66–69]
Erosion decrease	[22,23,27,68,69]
Soil moisture increase	[27,28]
Splash effect reduction	[46,68,69]
Soil roughness increase	[27,31,46]
Soil sealing decrease	[27,31,46]
Effect on vegetation	
Decrease of sappling mortality	[26,28,69]
Increase of available water for plant	[26]
Reduce hydrological plant stress	[26,28,69]
Plant height increase	[26,28,69]
Diameter of the canopy increase	[26,28]

an organic mulch were higher with doses of 3 Mg ha^{-1} compared to 10 Mg ha^{-1} in Mediterranean cultivated conditions. Other studies have shown that soil organic carbon increments depend on the chemical composition of the amendment [49–52]. Therefore, with similar application rates, increases in soil organic carbon will be different in soil amended with either straw mulch or chicken manure due to the high amount of lignin and cellulose existing in these types of mulch [52]. Another factor to consider in the process of mineralization is the degree of composting previous to its application [45]. According to a study based on amendment mineralization rates with different degrees of composting [53], high level of composting resulted in higher soil organic carbon increments [26].

Moreover, the effects on amendment on soil nutrients availability are highly influenced by the rate of mineralization. For some nutrients, such as nitrogen, phosphorus and sulfur, this effect is mainly dependent on the C/N, C/P and C/S ratio, respectively [54–58]. Regardless of decomposition rate of the soil amendment and increase in soil organic carbon, a direct consequence derived from the use of this amendment is a reduction in the bulk density and increase of porosity along the soil profile [59–61]. In addition, other studies have shown positive effects on the number of aggregates and their stability [61–63]. This can largely be explained by the formation of new complexes between soil particles and organic matter [56,58,64]. Using organic amendments can also increase the soil water holding capacity and have positive effects on vegetation growth [65]. Hueso-González et al. [26] showed an increase in the availability of water after amendment addition that resulted in higher seedling survival (more than 50% compared to soil without amendments). Additionally, the incorporation of organic materials usually increases cation exchange capacity [62].

Regarding the hydrological consequences of amendment application to soils, there are studies in which organic amendments have been suggested to protect soil from rainfall and runoff forces when vegetation is absent [66–68]. Some studies have indicated the effectiveness of mulch to increase surface roughness and reduce soil losses compared to control soils under semi-arid conditions [46]. With higher soil roughness, overland flow velocity is reduced and higher infiltration rates are produced, resulting in a large decline in soil erosion rates [27,69].

Conclusions

Drylands are one of the most susceptible biomes to degradation and therefore restoration of these ecosystems will become critical to prevent desertification in future scenarios of increased aridity. The use of organic amendments can enhance soil quality and reduce use of chemical fertilizers. However, the effects of this strategy on soil properties will largely depend on the amendment origin, doses, stability and maturity of the organic material and the application method. Different organic amendments have been proposed as restoration techniques ranging from mulch to organic waste and biofertilizers. The application of combined amendment types have demonstrated better results in soil fertility than their individual application. Regardless of the selected type of amendment, the stability and maturity of the organic material needs to be considered. Application of unstable or immature organic amendments may induce adverse effects on soil properties. Organic amendments should always be applied at the minimum effective doses. The rate of modification depends on the final objective and the previous condition of soils. The most accepted method is application on the soil surface ("on top").

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