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Consequence of interaction between soil erosion processes and dryland landforms

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ABSTRACT

Soil is directly linked to climate through the exchange of carbon between the atmosphere and the pedosphere. Anthropogenic-geomorphic disturbances and accelerated soil erosion processes stimulate spatial heterogeneity in the distribution of soil biotic-abiotic components, causing the activation of positive feedback mechanisms that amplify small deviations and encourage large scale dynamics at the landscape level. Interaction between soil erosion processes and landform characteristics are thought to be the major factors contributing to the emergence of spatial heterogeneity in the biophysical and biochemical mechanisms controlling the linkage between the pedosphere and atmosphere. Dryland landscapes contribute a high proportion of CO_2 emissions from soil to the atmosphere due to large-scale heterogeneity in the distribution of vascular plants and surface concentrations of SOC. Here we reviewed recent contributions to the study of biotic and abiotic drivers of spatial heterogeneity in drylands, and we illustrated a holistic perspective of the interactions among soil erosion processes such as water-wind erosion and dryland landforms characteristics and their impacts on instability in the CO_2 concentrations of the atmosphere and, subsequently climate change.

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1. Introduction

A characteristic of the degraded landscapes is the simultaneous emergence of heterogeneous states in the same range of environmental conditions that can differently respond to disturbance regimes (Veraart et al., 2012; lenton 2013). Aridland landscapes are the typical examples of such systems. Interaction between soil erosion processes and landform characteristics is one of the most important causes of the emergence of spatial heterogeneity in the distribution of soil biotic-abiotic components in small spatial scales within drylands.

Heterogeneity refers to variation in space and statistically express as spatial variance > 0 that is contrasts with homogeneity (spatial variance= 0) (Wiens 1995). Although spatial heterogeneity has long been considered a key determinant of biodiversity (Katayama et al., 2104; de Souza Júnior et al., 2014), previous studies have reported negative and positive effects of landscape heterogeneity in dynamic trends of ecosystems (Levin et al., 2007; Fahrig et al., 2011). The negative effect of spatial heterogeneity is often reported as an outcome of fragmentation of landscape biotic-abiotic components. A positive consequence of spatial heterogeneity in dryland landscape is the simultaneous emergence of local scale states as degraded mosaics and degradation-prone patches that exhibit different resilience degrees due to the different functioning. Such heterogeneities affect the biophysical and biochemical mechanisms controlling the resilience level of the states in the face of environmental harshness.

Interactions between soil erosion processes and landform characteristics are thought to be the major factors contributing to the emergence of spatial heterogeneity in the biophysical and biochemical mechanisms controlling the linkage between the pedosphere and atmosphere. Climate change will likely modify current precipitation regimes affecting the global carbon cycle in relation to erosion processes. Soil erosion processes, in turn, have significant impacts on the redistribution and transformation of soil organic carbon and, subsequently, its mineralization and sequestration across a landscape. Therefore, interactions among soil erosion processes, such as hydrological and aeolian processes and terrain indices associated with dryland landform structure stimulate localized variations in soil biotic and abiotic components, disturbing the soil C flux balance. Apart from global warming, the major cause of dryland degradation is generally soil and vegetation erosion by many processes such as different types of landslides, land subsidence, and hydro-aeolian disturbances that are the obvious examples of erosive processes in drylands. These processes with the asymmetric redistribution of water, nutrients, and sediment occur the spatial heterogeneity in the structuring and functioning of the landscape. One of the critical consequences of spatial heterogeneity in arid regions is the activation of positive feedback processes (Fig. 1). These processes amplify significant variations in the biophysical and biochemical mechanisms controlling the linkage between the pedosphere and atmosphere. Previous empirical studies have reported the role played by many dominant disturbances of arid regions in the activation of positive biotic-abiotic interactions associated with spatial heterogeneity. Ravi et al. (2007, 2009 and 2010) have shown the role of hydro-aeolian processes in the occurrence of heterogeneity in soil and vegetation patterns across the arid landscape. They expressed how these heterogeneities with the activation of amplifying positive feedback mechanisms can promote land degradation trends in arid regions. Geertsema et al. (2009) have shown how landslide as a geomorphic disturbance with changing site, soil, and vegetation can provide biodiversity at the landscape level. Mohseni et al. (2017) have reported how the expansion of land subsidence-related ground fissures with the occurrence of spatial heterogeneity and change of ecological feedbacks within the landscape can result in multiple stable states and, subsequently more degradation toward the desert state. Mohseni et al. (2019) have studied the role of debris flows as a geomorphic disturbance in the emergence of heterogeneities in soil biotic-abiotic properties and, subsequently their functions on climate change.

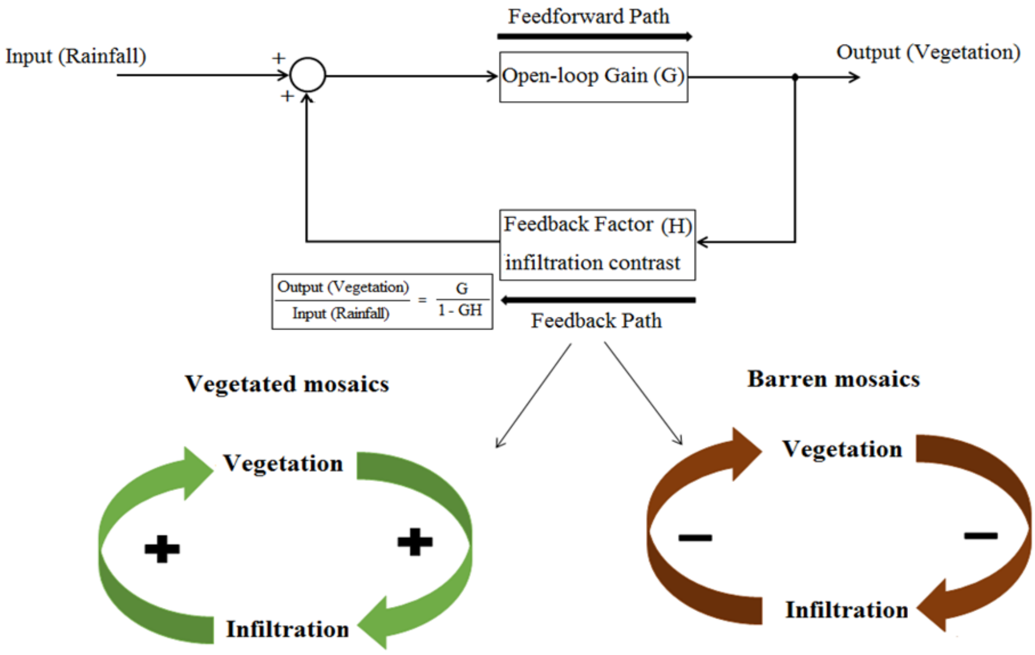

Fig. 1. Conceptual diagram of some positive biotic-abiotic feedback loop in arid ecosystems showing shift between two different states.

2. Material and Methods

In this research, we highlighted that the interactions between soil erosion processes and landform structure could cause small scale variations in the functioning of biochemical mechanisms within heterogeneous mosaics that have a critical role in the linkage quality between the pedosphere and atmosphere. Such conditions can exhibit paradoxical impacts on soil C cycling, via the simultaneous emergence of hot spots of soil C reservoir and CO_2 flux in adjacent landform positions. It can be assumed that if the relationship of CO_2 flux and biotic–abiotic variables of the soil is consistent throughout the landform, erosive soil disturbances would create only a net carbon loss.

3. Results and discussion

3.1. Interaction between soil erosion processes and landforms, and their consequences

3.1.1. Water-wind erosion and coppice dune dynamics

The dynamics of the formation and evolution of vegetated coppice dunes are example of the interactions between wind-water erosion and micro-geomorphology and their impacts on the activation of positive feedback processes controlling biochemical mechanisms affecting CO_2 dynamic in a small spatial scale. Coppice dunes or nebkhas are recognized as one of the most common geomorphic landforms in the many global arid and semiarid regions, which profoundly affect organic carbon dynamics in these ecosystems (Hesp and Thomas, 2017). Shrub nebkhas cause considerable accumulation of soil nutrients, thereby encouraging soil biological diversity and preventing soil resource loss (Luo et al., 2020). The formation and evolution of nebkhas extensively depend on the relationship between aeolian and hydrological processes and shrub canopy (Li et al., 2020). These abiotic processes in interaction with the dunes' micro-geomorphology encourage the spatial heterogeneity in the distribution of sediment aggregate size along an interdune-dune continuum. Some studies showed that the nebkhas are mainly made of coarse sediments due to the saltation of sand particles driven by the wind while, internebkha spaces mainly compose of fine aggregates such as silt and clay (Li and Ravi, 2018). Other studies confirmed that the internebkha sediments contain more sand than the dunes (Langford, 2000). However, different geomorphic positions of a dune, including leeward and downwind slopes, top, and edge positions, exhibit significant variations in sediment aggregate size distribution (Fig. 2). Such variations within a coppice dune system stimulated by the interaction between hydro-aeolian processes and micro-geomorphology can significantly affect the sediment physiochemical properties. The condition affects biochemical mechanisms controlling the mineralization and sequestration of SOC within different geomorphic positions of a dune. Wind and water erosion in the interaction with the coppice dunes' micro-geomorphology exhibit a selective removal and redistribution of soil and sediment fraction. The accumulation of aggregates with different sizes along the internebkha-nebkha continuum can exhibit the contribution of different soil erosion processes in sediment transport and deposition. The interaction among hydro-aeolian processes and micro-geomorphology can vary biophysical mechanisms controlling the C mineralization rate within the different coppice dune positions. As other studies have shown (Li and Ravi, 2018), average aggregate size reduce from the internebkha areas to the nebkhas, and the finest aggregates (i.e., fractions that the wind is not able to carry them) can be seen observed on the dune edge, illustrating the functioning of hydrological processes on the evolution of the nebkha structure. Many researches have confirmed that sediment-laden runoff occurs in the internebkha areas (Eldridge and Rosentreterand, 2004), which are significant deprescsions that act as playa compared with the nebkha structure. This condition allows the convergence of runoff and, subsequently transportation of finest particles from the interdune areas to the edge of the nebkha. As a result, the accumulation of finest aggregates at the dune edge can be an outcome of the horizontal sediment transport by surface runoff from the internebkha areas to the nebkhas, as well as the vertical transport of nutrient-rich sediments down a slope. This delivery of fine sediments to the dunes provides a condition for the accumulation of nutrients, organic matter, and subsequently outside enlargement of vegetation at around the dune edge. So that, the labile fractions of OC can bond with clay fractions and exchangeable cations to contribute toward the formation of soil aggregation (Desrochers et al., 2020). These conditions facilitate higher sediment stability, and subsequently enhanced physical protection on labile organic carbon against the microbial respiration in the dune edge. This condition does not show in the top and downwind positions of the dunes due to the significant increase of sand fraction transported by aeolian processes that cannot physically protect OC against microbial decomposition (Bryan, 2000; Nadeu et al., 2011). Therefore, variability in sediment grain-size distribution affected by the interaction between hydrological-aeolian processes and micro-geomorphology can considerably affect the level of physical protection on SOC against microbial decomposition via the formation of soil aggregation, causing the appearance of hot spots of CO_2 flux and reservoir within the nebkhas. The observed patterns of sediment aggregate size distribution, in combination with the CO_2 efflux pattern and the associated variables along the interdune-dune continuum, allow us to develop a conceptual model that can explain the impacts of the interaction among the hydro-aeolian processes and micro-geomorphology on the emergence of hotspots of sediment CO_2 reservoir and flux within different positions of the dunes.

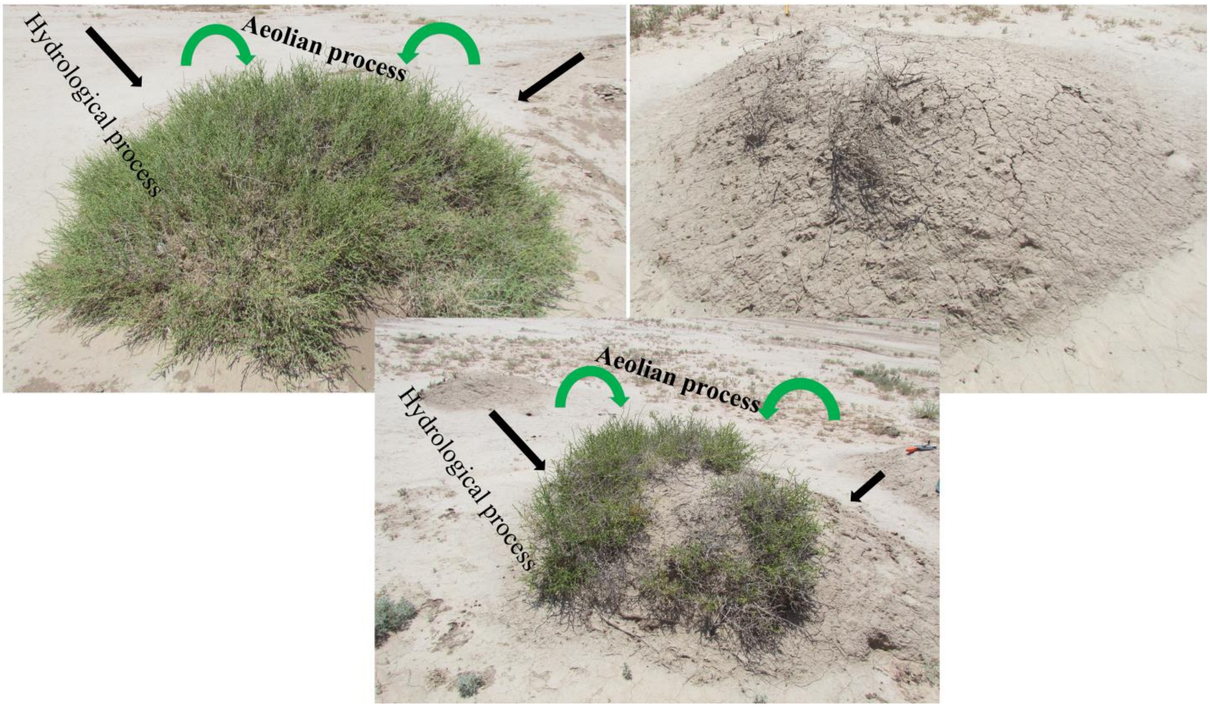

Fig. 2. Interaction among hydrological and aeolian processes and nebkha structure resulting in the formation, expansion, and collapse of vegetated coppice dun pattern. The black arrows and curved green arrows illustrate hydrological processes (runoff and infiltration) and aeolian processes (erosion and deposition), respectively.

3.1.2. Dynamics of landforms related to water erosion progression

The detachment and transport of soil particles by overland flow is one of the most important causes of land degradation (Ollobarren et al., 2016). The progression of water erosion patterns from rill to gully erosion significantly affects the level of soil aggregates degradation (Nael et al., 2004), and thereby stimulates change in the soil physical and biochemical properties controlling the soil organic carbon mineralization and sequestration level within the original soils eroded by rill and gully erosion. In initial erosion stages such as the rill erosion process, labile OC-rich topsoil-layer strongly removes by raindrop energy (Mueller-Nedebock et al., 2016). Rill head-cut migration and sidewall expansion affected by the overland flow, as the major driving forces in the formation of the gully, accelerates the development of rill channels into the gully, causing the degradation of larger amounts of OC-rich topsoil that is combined with soil subsurface layers poor in terms of OC (Nadeu et al., 2011). This condition degrades soil structure and weakens aggregate stability in the original soils eroded by gully erosion. Rill erosion process is restricted to the soil surface layers (Jiang et al., 2019). Although OC-rich topsoil transports into lowlands under the rill erosion, the lower transport capacity of this process causes a higher organic carbon accumulation in the eroded soils compared with gully erosion. These conditions facilitate higher soil stability, and subsequently enhanced physical protection on labile organic carbon against the microbial respiration in the original soils surrounding the rill areas compared with gully erosion, causing change in hotspots of flux and reservoir CO_2 under different water erosion patterns. This condition does not show in the gully area due to the high propensity of this erosion process to transport a larger amount of OC-rich topsoil that is combined with soil subsurface layers poor in terms of OC (Nadeu et al., 2011).

3.1.3. Dynamics of depositional landforms

Alluvial fans may be described as non-equilibrium landforms resulting from the spatial variability of sediments involved in different types of landslides, including debris flows, flash floods, sheet floods, other hyperconcentrated flows. Detachment and transportation of surface soils along the slope, as well as the simultaneous erosional-depositional nature of the landform cause the alluvial fans to exhibit a contradictory environment in terms of biological, hydrological, and edaphic patterns along the small-scale spatial intervals. Such the spatial heterogeneity due to the interactions among soil erosion processes and landform structure result in these landforms illustrate the paradoxical role in spatial variability of soil C flux. The heterogeneous redistribution of landslide-related resources plays a crucial role in the localized distribution of inorganic/organic carbon stimulating spatial variability in soil C storage and CO_2 flux along different slope positions. In the lowland positions where sediment transported by debris flow is deposited by the water sinking into the soil due to the decreased slope gradient and elevation, a significant accumulation of fine fractions can be seen, which provides a stable environment for the development of biological soil crust. Conversely, increasing coarse fractions and, subsequently decreasing soil moisture at the higher elevations and steeper slopes do not support the formation of the biological crusts for the upland microhabitats. These asymmetric biophysical conditions explain the significant differences in chemical patterns and soil nutrients between the positions. The interaction between water erosion and landform micro-geomorphology affects the relationship pattern between spatial variability of soil C flux and relevant physiochemical properties via small-scale spatial variances in the landscape functioning. The spatial heterogeneity causes the emergence of differences in the factors controlling soil CO_2 flux rate over adjacent landform micro-zones. Changes in the biogeochemistry of the soil induced by the interaction between the heterogeneous redistribution of debris flow sediment and geomorphic factors such as elevation and slope, account for the local-scale variations in factors controlling soil CO_2 flux within the landform. As studies have shown (Mohseni et al., 2019), the decreased soil CO_2 flux rate in the lowland position, despite increasing microbial activity, demonstrate a significant and negative relationship to the increased inorganic C concentration and pH, which may be explained by the fact that the alkaline environment formed by the lowland deposition of sediment favors the exchange of organic C to carbonate production (Thomas et al., 2014). This implies that the fine particle concentrations on the lowland soils, as well as the CO_2 generated by moss respiration (or OC decomposition) bond with alkaline cations to contribute toward carbonate production. Other researches (Xiao et al., 2018) pointed out that removal of OC from eroding positions can lead to the emergence of an environment of OC-rich sediment at depositional positions if soil moisture and limited oxygen be sufficient to inhibit microbial activities. In such conditions, depositional locations can be a source for OC storage (VandenBygaart et al., 2015). The findings illustrate the high propensity of lowland soils to capture mineral forms of C, other than the organic forms, due to runoff-runon mechanism generated by the debris flow (runoff sediment-laden water from the erosional positions and runon onto of the depositional positions) encouraging the emergence of hot spots of soil C storage within the alluvial fan. Due to the erosional nature of high elevations and steep slopes, this condition cannot occur in the upland positions, and consequently, the upland microhabitats exhibit hot spots of CO_2 emissions from soil to the atmosphere. As a result, the fragmentation of soil aggregates and subsequent losses of organic C in erosional positions can be an inhibitor cause for plant growth and biological crusts in the upper positions (Wei et al., 2016). Conversely, the deposition of nutrient-rich sediments following heterogeneous resources redistribution along the slope (runoff mechanism) can increase the proportion of microbial community at depositional positions (Huang et al., 2013; Li et al., 2015; Xiao et al., 2018). Therefore, significant interactions between soil erosion processes and landform structure encourage local scale variations in the structuring and functioning of different landform positions, disturbing the soil water content-soil CO_2 flux equation via the occurrence of other regulatory controls at points with higher moisture content. The condition that can stimulate the emergence of hot spots of soil C reservoirs, as opposed to with the high C emissions of the other positions. Landform structure-dependent geomorphic disturbances, such as landslide, through changes to the biochemical mechanisms can exhibit paradoxical impacts on soil C cycling, as the simultaneous emergence of hot spots of soil C reservoir and CO_2 flux in adjacent landform positions. It can be assumed that were the relationship of soil CO_2 flux and soil biotic-abiotic variables consistent throughout the landform, undoubtedly erosive soil disturbances would create only a net carbon loss.

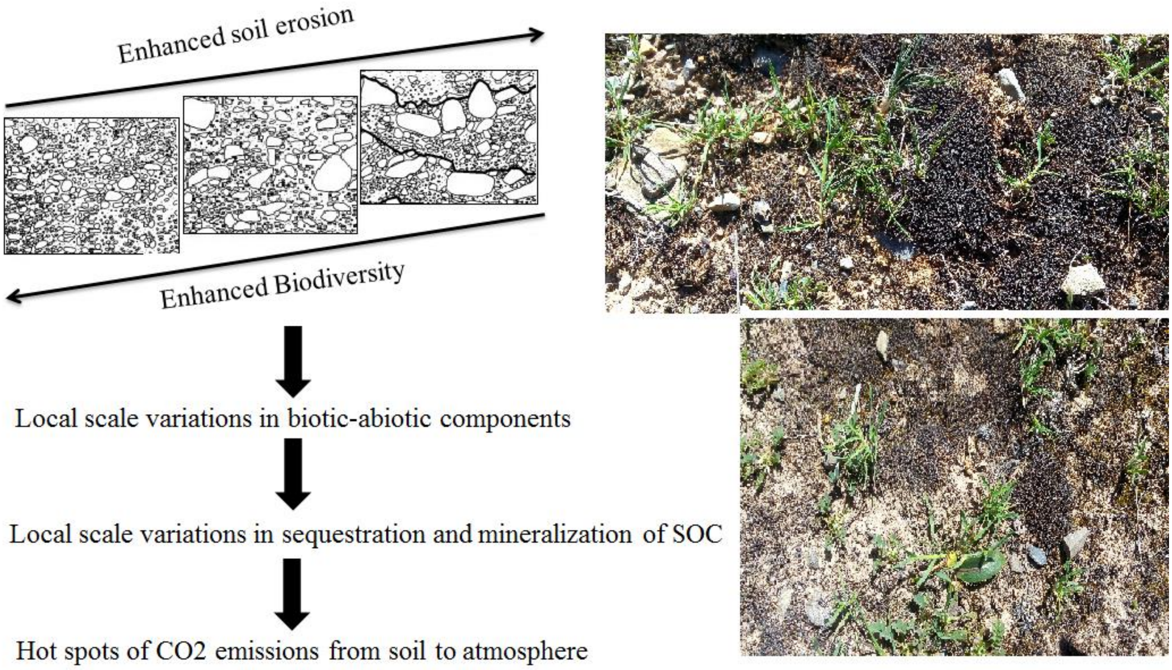

Fig. 3. Conceptual diagram illustrating the relationship between edaphic characteristics, soil erosion rates, biodiversity and climate change along an aridland landform.

4. Conclusion

A characteristic of the degraded landscapes is the simultaneous emergence of heterogeneous states in the same range of environmental conditions that can differently respond to disturbance regimes. Aridland landscapes are the typical examples of such systems. Soil erosion processes are thought to be the major factors contributing to the emergence of spatial heterogeneity in the biophysical soil variables. These processes have significant impacts on the redistribution and transformation of soil organic carbon and, subsequently, its mineralization and sequestration across a landscape, affecting the global carbon cycle. Interactions among soil erosion processes, such as hydrological and aeolian processes, and terrain indices associated with dryland landform structure stimulate localized variations in soil biotic and abiotic components, disturbing the soil carbon flux balance. This study showed how the interaction between soil erosion processes and landform characteristics could encourage the emergence of spatial heterogeneity in the distribution of soil biotic-abiotic components, causing small scale variations in the functioning of biochemical mechanisms within heterogeneous mosaics that have a critical role in the linkage between the pedosphere and the atmosphere. Such conditions could exhibit paradoxical impacts on soil carbon cycling, via the simultaneous emergence of hot spots of soil carbon reservoir and CO_2 flux in adjacent landform positions. It can be assumed that if the relationship between CO_2 flux and soil biotic–abiotic variables is consistent throughout the landform, erosive soil disturbances only would create a net carbon loss.

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