Annals of Arid Zone 57(3&4): 65-73, 2018

Evaluation of the Conceptual Model on Shrubbiness-Desertification on Arid Rangelands

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Received: April 2018

Abstract: Advancement of shrubbiness (increase in plant cover and density of woody species) on different environments world-wide has generated an increasing interest in the scientific community, particularly because of its association with the desertification process which is increasing, also at a world-wide level. There are two opposing positions, both of them validated by scientific evidences. The greatly accepted position recognizes shrubbiness as one of the mechanisms conducive to desertification in natural environments, cataloguing it as a negative process. A different view, based on recent studies, suggests that shrubbiness should be considered as a positive process because it may drive a reversal of desertification, depending on the environment and the species of shrub studied at a site. This review presented within this framework discusses the existing relationship between shrubbiness and desertification and proposes an approach that should be considered in future research.

Key words: Shrubbiness, desertification, arid rangelands, arbuscular mycorrhiza, soil biological crusts.

Land Degradation and Desertification World-Wide

Arid and semi-arid ecosystems represent approximately 41% of the terrestrial surface area and harbor more than 38% of the world population (Reynolds *et al*., 2007). Between 10 and 20% of these ecosystems present some type of severe degradation (MEA, 2005). It is expected that the percentage will increase substantially as a result of the climatic change and population growth.

In the last two decades, the process of shrubbiness and the advancement of desertification in various ecosystems has generated considerable interest in the scientific community world-wide. Shrubbiness consists of an increment in density, cover and biomass of species of shrubby growth habitat on environments dominated by herbaceous species (Haubensak and Parker, 2004; van Auken, 2009). Desertification, on the other hand, implies soil degradation on arid, semi-arid and subhumid-dry areas, with negative ecological and socio-economical consequences, and as a result of, at least partially, anthropic activities (Reynolds *et al*., 2007). Changes in the biotic and abiotic environments; increases in soil erosion; reductions in the structure, sustainability and/or ecosystem functioning in the long-term and irreversible losses in primary and secondary productivities are typical signs of desertification (MEA, 2005).

The proliferation of shrubbiness on grasslands has been reported in arid, semi-arid, temperate, alpine and artic environments in the whole world (van Auken, 2000). However, this phenomenon has been mostly studied on ecosystems where the transition between grasslands and shrublands has been dramatic and difficult to reverse during the last 150 years (van Auken, 2009; Maestre *et al*., 2009).

It is estimated that 13 million ha are under the effect of shrubbiness in the south of Africa (Roques *et al*., 2001), while such a surface will reach to 330 million ha in the United States of America (Knapp *et al*., 2008). Similar scenarios have been reported in Australia (Robinson *et al*., 2008), India (Singh and Joshi, 1979) and South America (Adámoli *et al*., 1990).

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The transition from a grassland to a shrubland environment has been associated with changes in the spatial-temporal distribution of the soil and vegetation resources, thus creating a more heterogeneous environment (Schlesinger *et al.,* 1996; Schlesinger and Pilmanis 1998). The prevailing model of shrubbiness leading to a greater desertification on semi-arid grasslands was originally proposed by Schlesinger *et al.* (1990) for the Chihuahua Desert (United States). More than 20 years ago, these authors proposed that the heterogeneity creates opportunities for the colonization of new shrubs. This is because it reinforces itself at the same time when the abiotic (e.g., nutrient transportation, water availability) and biotic (e.g., root and microbial activities) mechanisms determine a mobilization of soil resources, which accumulate under the shrub cover favoring greater water infiltration levels (Bhark and Small, 2003; Ewing *et al.,* 2007; Busso and Bonvissuto, 2009; Busso *et al.,* 2012). In turn, the bare areas between these vegetated areas experience high temperatures and evapotranspiration, delayed incorporation of inorganic N, denitrification, ammonia volatilization, moisture reduction and infiltration, and subsequent erosion increase (Schlesinger *et al.,* 1990; Parizek *et al.,* 2002; Darrouzet-Nardi *et al.,* 2006; Busso and Bonvissuto, 2009). The combined effect of these processes results in a mosaic of impoverished areas among shrubs and a strengthening of fertility islands which are formed between the bare sites (Schlesinger *et al.,* 1996; Busso and Bonvissuto, 2009). This makes those shrublands extremely resistant to changes, increasing their persistence and development at the expense of grasslands (Schlesinger *et al.,* 1996; Giorgetti *et al.,* 1997). These disturbances in the structure and functioning of ecosystems will finally lead to desertification (Schlesinger *et al.,* 1990; Archer *et al.,* 2001). In comparison to the original grassland, the popular view, for example, is that shrublands are associated with a reduction in plant biomass, diversity and species richness (Zarovalli *et al.,* 2007; van Auken, 2009).

Disputes about the causes of shrubbiness of semi-arid grasslands have historically been a subject of debate. It has centered, lately, on the climatic change and the atmospheric CO_2 increases (Naito and Cairns, 2011). However, most of the density increases of woody species has been associated with high herbivory levels (van Auken, 2009). Overgrazing of areas with a shrubby component normally leads to an increase in the dominance of shrubs and the conversion of grasslands to less desirable shrublands (León and Aguiar, 1985; Milchunas and Laurenroth, 1993; Bóo *et al.,* 1997). Excess herbivory reduces the aboveground and belowground biomass, cover and vigor of the desirable perennial grasses (Kröpfl *et al.,* 2007), leading to a reduction in the amount of fine plant fuel. This results in a reduction of the frequency (or even the elimination) of natural fires on grasslands and shrubby steppes. These fires would have otherwise contributed to the control of the density of woody species and prevent the invasion of new areas (Bóo *et al.,* 1997; Peláez *et al.,* 2010). In addition, livestock and the local fauna would favor the dispersion and germination of seeds of some woody species (van Auken, 2000; Cabral *et al.,* 2003).

The paradigm of desertification puts great emphasis in the advancement of shrubbiness on grasslands. This comes from the fact that shrubbiness and desertification in the Chihahua desert, where most research was conducted to develop of the conceptual model of shrubbiness-desertification, are very intimately linked (Schlesinger *et al.,* 1990; Peters *et al.,* 2006). The loss of soil fertility, a result of shrub species advancement, is considered as a precursor of desertification by ecologists world-wide (Archer, 2010). Because of this, it is possible to find various works in the literature that point to shrubbiness as the maximum ecological expression of desertification in arid and semi-arid rangelands (Archer *et al.,* 2001; Peters *et al.,* 2006). The view that prevails between agropecuarian producers and scientists is that shrubbiness and desertification are, as a result, synonymous (Eldridge *et al.,* 2011). However, recent studies allow a unique interpretation of shrubbiness leading to ecosystem improvement (Maestre *et al.,* 2009). In an updated revision of 244 works coming from all over the world (including 7 works from Argentina), Eldridge *et al.* (2011) evaluated the effects of shrubbiness on 43 response variables (structural and functional). They found that positive and neutral effects of shrubbiness were more abundant than negative. Their results demonstrated that the increment in the cover of woody species was associated with decreases in the grass cover and the soil pH. Nevertheless, that increment was also associated with increases in aboveground and total organic C, total N, exchangeable soil Ca, available P and the potential mineralization of soil N. Shrubbiness additionally increased root biomass in the first 0-15 cm of the soil profile. At the same time, density of vegetation patches and richness of vascular plants were not affected. Maestre *et al.* (2009) observed results (in Mediterranean rangelands in process of shrubbiness) opposite to those reported by Schlesinger *et al.* (1990). The authors neither found evidence of shrub-induced modification of the spatial distribution of the plant species nor the soil microorganisms, nor that nutrients were transported from the uncovered spaces to below the shrub cover in such ecosystem. On the contrary, they observed a greater species richness, diversity, evenness of perennial species and a greater fertility at sites with shrubs, in both covered and bare areas. In rangelands, an increased species richness improves productivity (Tilman *et al.*, 2001), while a greater plant diversity increases resource use efficiency, contributing to stability in the functioning of ecosystems especially when these are under stress (Oesterheld, 2008; Loydi and Distel, 2010). In this regard, a recent study which involved the participation of 53 researchers of 16 countries (including Argentina), has proposed the importance of plant diversity preservation (herbaceous and woody) in arid and semi-arid regions to alleviate the effects of the climatic change and desertification (Maestre *et al.*, 2012). As a result, at least in some environments, the advance of shrubbiness would contribute to a reversion rather than an increase of the desertification.

The degree at which shrubbiness leads to a degradation and desertification depends upon the particular identity of the shrubby and herbaceous species on the site (Peters *et al.*, 2006; Maestre *et al.*, 2009, 2016; Eldridge and Soliveres, 2015). Differences in physiology, aboveground and belowground architecture, distribution of the vertical biomass on shrubs and involved grasslands can generate different patterns of retention and distribution of the mobile resources depending on the species involved (Eldridge *et al.*, 2011). In Australia, it was observed that the same species of invasive shrubs determined a positive impact on the functional indicators of an herbaceous grassland and a negative impact on another one (Ayers *et al.*, 2001). Because of this, it is critical to evaluate shrubbiness effects on each particular community before adopting a generalization on the existing relationship between shrubbiness and desertification. In addition, most research on shrubbiness is usually biased toward the livestock production systems. As a consequence, reductions in primary and secondary productivities are directly viewed as analogous to degradation or desertification (Maestre *et al.*, 2009, 2016; Eldridge *et al.*, 2011).

Soil fertility directly depends on its microbiological activity in any ecosystem, which in turn is influenced by changes in plant species composition (White *et al.*, 2000). In some environments, shrubbiness has created very marked differences between shrubby and bare sites, altering the microbial composition and reducing the diversity of fungi and bacteria, which directly affects soil fertility (Herman *et al.*, 1995; Smith and Johnson, 2004; Zachary *et al.*, 2008; Yannarell *et al.*, 2014). However, in other shrubby ecosystems, either increments or absence of negative effects in the microbial activity and diversity (Cable *et al.*, 2009; Jin *et al.*, 2011; Maestre *et al.*, 2011; Qu *et al.*, 2016) and in the soil C and N mineralization rates (Asner *et al.*, 2003; Haubensak and Parker, 2004; Baer *et al.*, 2006; Zavaleta and Kettey, 2006; McKinley *et al.*, 2008; Throop and Archer, 2008) have been observed. These results indicate that soil fertility may not be compromised and it might even increase in some cases, in these environments. Increase in the production of root biomass, of litter and root exudates, and the hydraulic lift on woody species would be responsible, at least partially, for the observed positive effects (Maestre *et al.*, 2009).

In low productivity environments, arbuscular mycorrhiza (AM) and the soil biological crusts (SBC) would be of major interest. The arbuscular mycorrhizal fungi (AMF) form hyphae, vesicles (in some species) and arbuscules (interchange structures) within the cortical cells of the plant they colonize (Parodi and Pezzani, 2011). In this association, the plant provides photoassimilates (i.e., C sources) to the fungi and they provide water and nutrients (mostly P, as long as the availability of this nutrient is low) to the plant (Barrer, 2009). The hyphae of AMF are physiologically more efficient for water and nutrient uptake than plant roots (Montaño *et al.*, 2007), providing a greater resistance to water and nutritional stresses (Schreiner *et al.*, 1997). Research conducted in other parts of the world shows diverse results in the response of soil fungi in general and of AM in particular, in shrubby environments, also depending on the identity of the fungi species and of plant species composition (Azcón-Aguilar *et al.*, 2003; Yannarell *et al.*, 2014). On the other hand, the SBC represent intimate associations among soil particles, cyanobacteria, algae, fungi, mosses, hepatical and bryophytes. However, their composition varies depending on the climatic regime (Belnap and Lange, 2003).

Though SBC have been found in arctic, boreal and arid ecosystems, it is in these last-mentioned ecosystems where SBC have a greater ecological importance since they can cover up to a 70% of the soil surface area (Belnap and Lange, 2003). Several positive effects are associated with the SBC: The stabilization and protection of the soil against erosive processes; the increase in water infiltration and soil moisture retention (favoring the germination and establishment of new seedlings); the fixation of atmospheric CO_2 and subsequent release because of lixiviation and decomposition; increases in the concentrations of organic matter, N, Mn, Ca, K, Mg and available P (Eldridge and Rosentreter, 1999; Belnap and Lange, 2003; Castillo-Monroy and Maestre, 2011). According to a recent study, the acquisition of nitrate and ammonium by plants would require a smaller root growth in soils covered by SBC than in soils covered by grasses or woody species (Delgado-Baquerizo *et al.*, 2013). Anyhow, these results cannot be extrapolated to all areas where SBC are present. The presence of SBC has been described in Argentina (Scutari *et al.*, 2004) and particularly at the south of the Phytogeographical Province of the Monte (Kröpfl *et al.*, 2007; Calabrese *et al.*, 2013). However, the scarcity of local studies on the persistence of SBC and AM communities in particular and of soil microorganisms in general and their relationship with soil fertility in shrubby environments restricts their contribution towards restoration of degraded environments.

Grasslands of Argentina are not immune to the phenomenon of shrubbiness where 75% of the continental territory is characterized by the presence of arid and semi-arid zones and the industry of livestock production is dependent on grazing of native vegetation (Busso and Fernández, 2018). Examples of the advancement of shrubbiness on productive zones have been reported in various regions of the country (Adámoli *et al.*, 1990; Parizek *et al.*, 2002; Cabral *et al.*, 2003; Anriquez *et al.*, 2005; Kröpfl *et al.*, 2007; De Villalobos *et al.*, 2011; Dussart *et al.*, 2011). In the particular case of Southwestern Buenos Aires, changes produced in the native landscape are mostly derived from the advancement of the agropecuarian borders. This has resulted in a reduction in the cover of perennial grasses and a reduction in the frequency of usual fires in the region. Because of this, a shrubbiness system has eliminated the grassland as a production system (Kröpfl *et al.*, 2007; Peláez *et al.*, 2010; Peláez, 2011; De Villalobos, 2013). About 75% of District of Patagones (554.138 ha; Giorgetti *et al.*, 2006) has exclusive livestock activity, where it is common to observe continuous grazing with an excessive stocking rate (Fernández *et al.*, 2007). In addition, the precipitation regime in this system, with the greatest precipitation concentrated in fall and summer, and without torrential events, allows the deep recharge of the soil in normal years, favoring shrubs rather than grasses (Kröpfl *et al.*, 2007). The process of degradation in the District of Patagones has not yet reached limits such as the ones occurring in other arid and semi-arid areas of the country, where desertification is already an irreversible phenomenon (Peláez, 2011). In the region, the ecological systems and the grassland species still exist; however, if current tendencies persist the scenario might become irreversible in a few generations. As a result, it is a priority to know the current stage of the advancement of shrubbiness, its real influence on the herbaceous stratum and soil fertility, and its relationship with the desertification observed in the region. In this way, it will be possible (1) to revise ecological concepts with respect to shrubbiness and desertification, (2) reformulate protection guidelines, use and management of these environments with the purpose that they are productive in the short-term and sustainable in time, and (3) propose reforestation program on cleared areas, with native shrubby species with forage value.

Towards a Better Understanding of the Shrubbiness-desertification Process

In Central Argentina, a combination of environmental (droughts, strong winds, unpredictable precipitation events) and anthropic (woody vegetation clearing, excessive soil tillage, overgrazing) factors have led to an increased land degradation coincident with the appearance of desertification processes (e.g., an increased soil erosion, and loss of its fertility and net primary and secondary productivities) (Peláez, 2011; Busso and Fernández, 2018). Under this scenario and given the fragility of the system, conservation of the woody plants, which serve as a structural skeleton for the herbaceous component, can result in a viable alternative for controlling the desertification process (Bogino *et al.,* 2002). Further, preservation of plant biodiversity has been demonstrated to be a useful tool for mitigating desertification in arid and semi-arid areas. In these ecosystems, the activity of the soil microbial communities (responsible for the organic matter decomposition and nutrient cycling), the arbuscular mycorrhiza (symbiotic association between the soil mycorrhizal fungi and the 95% of the terrestrial plants) and the soil biological crusts (symbiotic association between different soil organisms) play a critical role on plant growth and survival, and on the maintenance of plant diversity and productivity, promoting the stabilization and protection of the soil from erosive processes (Belnap and Lange, 2003; Kardol and Wardle, 2010; Martínez García, 2011).

Several efforts by our research group have demonstrated the importance of conserving the shrubby vegetation patches in an arid zone to prevent accelerated soil erosion and desertification of the ecological system (Busso and Bonvissuto, 2009; Busso *et al.,* 2012). In addition, because of plant biodiversity, in arid and semi-arid environments, would be critical to reduce the effects of climatic change and desertification (Maestre *et al.,* 2012), it is important to generate knowledge that promotes plant resource conservation in arid zones considering both the herbaceous and the shrubby components. Results obtained by our research group indicate that soil fertility and thereafter the productivity of some species, would increase as species richness and biodiversity of herbaceous and woody species also increases (Cardillo *et al.,* 2018).

The disciplines included by the members of our research group currently involved in the study of the shrubbiness-desertification process covered (1) the study of ecophysiological characteristics and rangeland management, (2) changes in the community of arbuscular mycorrhizal fungi after fire and defoliation in semi-arid rangelands, (3) capture, viability and determination of spores of mycorrhizal fungi species, (4) recognition and classification of plant species, (5) microbial respiration and soil nitrogen mineralization, (6) molecular analysis of soil microorganisms, (7) shrubbiness effects on the composition of soil microbial communities using various techniques: culture in selective media, and amplification and sequencing of genomic DNA, (8) use of current and historic satellite images to study the advancement of shrubby species, along with field studies to evaluate the reliability of the digital classifications.

Our ongoing research is evaluating the dynamics and the effects of shrubbiness on an arid rangeland within the context of desertification. This will contribute to increase our knowledge of the current shrubbiness stage and its relationship with the (a) distribution, diversity and species richness of the herbaceous vegetation, (b) soil fertility, (c) diversity, composition and functional characteristics of the soil microbial communities, (d) viability and diversity of spores of arbuscular mycorrhiza fungi and (e) cover by biological crusts. The obtained information shall allow the development of management guidelines and policies of vegetation and soil conservation that guarantee a sustainable use of the natural resources of the study region. In addition, our results will be an additional contribution to the current debate on the existing relationship between shrubbiness and desertification.

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Printed in December 2018