Can biological invasions induce desertification?

A common form of land degradation at the desert margins involves the rapid encroachment of woody plants into historic grasslands and the acceleration of soil erosion as a result of the loss of grass cover (Archer, 1989; Schlesinger et al., 1990). The conversion of perennial grasslands into desert scrublands has been documented worldwide (Van Auken, 2000; Ravi, 2008) and has important implications for regional and global biogeochemical cycles, climate, biodiversity and food security (Schlesinger et al., 1990; Knapp et al., 2008). However, this is not the only possible mechanism of land degradation driven by shifts in dryland plant community composition. Here, we present a new desertification paradigm that includes the invasion of stable desert shrublands by exotic annual grasses (Fig. 1). The mechanism we propose suggests that two major drivers of global environmental change, namely biological invasions and climate change, may act in concert and amplify each other's effect on land cover and soil resources.

Both shrub encroachment and exotic grass invasions affect the spatial distribution of soil resources (e.g. carbon, nitrogen and water) through altering fire regime and soil-erosion rates. The conversion of native perennial grasslands into shrublands increases soil resource heterogeneity as a result of hydrological and aeolian transport processes that cause significant resource redistribution (Schlesinger et al., 1990). Our studies in the shrub–native grass ecotone in the northern Chihuahuan desert have shown that fires can counteract the formation of this heterogeneity, in that the interaction of fires with soil erosion favors a more homogeneous distribution of soil resources (Ravi, 2008; Ravi & D’Odorico, 2008). Through a near-identical mechanism, invasion by exotic annual grasses can increase fire frequency, shrub mortality and soil loss, thereby destroying the heterogeneity of resources typical of desert shrublands and favoring the conversion into exotic (annual) grasslands. However, the long-term persistence of invasive grass cover may be restricted as a result of low-frequency recurrent droughts which displace these plant species that have not evolved in this regional climatic context (Salo, 1994; Martin-R et al., 1995). Drought-induced loss of vegetation cover is expected to be followed by even higher erosion rates and losses of soil resources. Thus, the process of degradation can be facilitated by the heterogeneity (shrub encroachment) and homogeneity (annual grass invasion) of resources, depending on the plant functional type inducing the change in resource distribution (Fig. 1).

In the desert shrublands of North America, exotic grass invasion is a major environmental issue, in that these grasses are found to increase connectivity between shrub patches, triggering periodic fires in systems without a fire history (D’Antonio & Vitousek, 1992; Brooks & Pyke, 2001). Interannual variability of precipitation, a common feature of arid landscapes, is thought to be a key factor determining the dynamics of invasion by annual grasses. In water-limited systems, invasive annuals initially benefit from a nurse plant effect, in that they establish on the resource islands existing beneath the shrubs and can reach high densities relative to native species during favorable years (Brooks & Pyke, 2001). In years of high resource availability, the invasive grasses are able to out-compete native species (Martín-R et al., 1995; Davis et al., 2000; Arriaga et al., 2004). Furthermore, in these preferential sites, invasives find higher soil water contents that may allow them to survive short periods of low rainfall in greater densities than natives. Many invasive grasses are found to demonstrate a higher phenotypic plasticity (i.e. the ability to alter their morphology and physiological processes in response to environmental changes) than native grasses (Funk, 2008), even in low-resource environments, which allows them to survive in unfavorable environmental conditions (and sites). Together, these features probably allow invasive grasses to consistently maintain larger densities associated with their developing populations compared with native grasses. Any decrease in the native species’ composition and in the functional type composition could lead to a further increase in susceptibility of the ecosystem to invasion by exotic species (Zavaleta & Hulvey, 2004).

In years of high precipitation, invasive grasses can spread into the interspaces, thereby establishing connectivity either between shrub islands or between shrubs and the sparse cover of native perennial grasses in the interspaces. Grass connectivity provides conditions favorable for the spread of fires typically induced by lightning in the summer months. It has been found that the effect of fires on soil properties results in the enhancement of soil erodibility. Our studies on fire-affected grasslands and shrublands in the southwestern USA have shown that fires increase wind-erosion rates in burned areas and that the increase in soil-erosion rates was considerably higher for shrublands than for grasslands (Ravi et al., 2007; Ravi, 2008). The erodibility of soils under burned shrub patches increased considerably after fire, whereas this postfire change in soil-erosion rates was negligible under grasses and bare interspaces. This enhancement of erosion processes was
attributed to postfire soil water repellency induced by vegetation, as this effect was absent in adjacent unburned areas with similar surface roughness and experiencing the same exposure to wind and water. The burning vegetation releases some organic compounds that induce different levels of water repellency in the soil, which are dependent on several factors, such as vegetation type, soil properties, fire intensity and duration (Doerr et al., 2000). Soil water repellency has been shown to affect the adsorption and retention of moisture in the soil, with important impacts on the interparticle bonding forces (Ravi et al., 2006). The weakening of these forces makes the surface soil more susceptible to erosion by wind and water. Thus, it can be concluded that in these systems sediment transport interacts with disturbances, such as fires, to affect the rates of soil erosion and resource redistribution.

In shrublands with invasive grasses, fires tend to counteract or limit the processes that reinforce heterogeneity in shrublands by activating the transport of nutrient-rich material from shrub-dominated resource islands to adjacent bare interspaces (Ravi et al., 2007; Ravi, 2008). Invasive grasses benefit from this rapid postfire availability of nutrients in the interspaces, as the invasive annual grasses are more effectively responsive to nutrient additions (e.g. nitrogen) than native perennials or annuals (Davis et al., 2000; Brooks & Pyke, 2001). Furthermore, an increase in resource availability that coincides with the availability of invading propagules is identified as a key factor that controls the invasibility of ecosystems by nonresident species (Davis et al., 2000). In this specific case, the increase of resources in the interspaces results from the postfire redistribution of nutrient-rich soils from the shrub islands, while invading propagules are available in the resource islands beneath the shrub canopies, where invasive grasses first establish. Fire-induced shrub mortality, along with the postfire redistribution of soil resources from the shrub resource islands (Ravi, 2008), provide ideal conditions for an increase in invasive grass cover, which, in turn, enhances connectivity, thereby increasing the frequency and intensity of fires. This fire cycle (D’Antonio & Vitousek, 1992) continues until the

![Fig. 1 Desertification induced by biological invasions. In this mechanism of desertification, first, the fire cycle allows invasive grasses to replace the shrub cover, and then drought-induced mortality determines the loss of vegetation cover, leaving the soil surface prone to erosion. The conceptual framework indicates that the process of land degradation can be facilitated by the heterogeneity and homogeneity of soil resources, depending on the plant functional type inducing the change in resource distribution.](image-url)
occurrence of drought conditions causes the widespread death of annual grasses. Because invasive annual grasses cannot tolerate low-moisture conditions, low-frequency recurrent droughts will result in the eventual loss of vegetation cover, thereby leaving the soil surface completely exposed to erosion processes and subsequent rapid irreversible losses of soil resources.

In landscapes invaded by exotic grasses, the degradation effects of droughts are intensified because there are very few preferential sites (fertile shrub islands) remaining for any plants to survive periods of low rainfall. This potentiates the landscape to resource and plant loss via the mechanisms described above. The invasion plant community composition will probably be maintained because rapid recolonization from nearby unburned sites is a strong possibility in wet years. Drought does not prevent the re-establishment of these grasses from the seed bank and populations expand rapidly during subsequent high-precipitation years. As a consequence, the invasive grasses are able to maintain a fire cycle (shrub mortality and resource homogenization) and prevent the re-encroachment of shrubs or native ephemerals (D’Antonio & Vitousek, 1992; Brooks & Pyke, 2001).

The landscape-degradation processes are accelerated by global changes, such as rising CO₂ concentrations in the atmosphere (Smith et al., 2000), which facilitate the establishment of exotic invasive annuals in previously inhospitable environments (shrublands). It has been predicted that many arid regions around the world – including the North American deserts – will become affected more frequently by recurrent droughts (Meehl et al., 2007; Seager et al., 2007). The resulting land-degradation processes, in turn, will reduce the capacity of the world’s drylands (i.e. c. 40% of the earth’s surface) to feedback and slow down anthropogenic increase in atmospheric CO₂ and the associated global warming.

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References


Ravi S. 2008. Feedbacks between fires and soil erosion processes at the desert margins. PhD Dissertation, University of Virginia, USA.


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