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What Drives the Conversion of Native Rangeland to Buffelgrass (*Pennisetum ciliare*) Pasture in Mexico's Sonoran Desert?: The Social Dimensions of a Biological Invasion

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Abstract The introduction of invasive exotic plants has many social dimensions. Although a diverse literature identifies some of the social drivers of exotic plant introduction and subsequent invasion, relatively little attention has been given to the motives of individuals involved. This research focuses on the extensive conversion of native rangeland to exotic buffelgrass (*Pennisetum ciliare*) pasture by ranchers in Mexico's Sonoran Desert using data gathered through systematic interviews and ordinary least squares regression modeling to demonstrate how a few social variables determine the extent of buffelgrass introductions. Results show that land allocation to pasture is determined chiefly by ranch size, with significant roles also played by rotational grazing, buffelgrass seed harvest, and exposure to government research. Results are contextualized and explored in depth, illustrating how the extent of rangeland-to-pasture conversion in this part of the Sonoran Desert is determined by direct and indirect social factors. The study also highlights implications for buffelgrass invasion.

Keywords Cattle ranching · Invasive alien species · Land-cover change · Land-use change · Range management

Introduction

A great amount of scientific, legislative, and public attention has recently focused on the movement of plants outside their native ranges (Henderson *et al*. 2006). In the United States alone, invasions by some 5,000 exotic plants affect millions of hectares of habitat and cost at least $33 billion annually (Pimentel *et al*. 2005). Beyond threats to agriculture, invasive exotic plants erode native biotic diversity, disrupt ecosystem processes, and compromise valuable ecological services (MEA 2005; Pejchar and Mooney 2009). The unprecedented rate and spatial extent of exotic plant invasion today can be attributed to the general dominance of the biosphere by modern human society (Turner *et al*. 1990; Vitousek *et al*. 1997; Ellis and Ramankutty 2008). A fine-grained and comprehensive understanding of the causes, dynamics, and consequences of plant invasion, however, requires attention to individual land managers. The research presented here adopts such a perspective, using the case of rangeland-to-pasture conversion in Mexico's Sonoran Desert to illustrate social drivers of the introduction and invasion of buffelgrass (*Pennisetum ciliare*).

Buffelgrass is one of several African pasture species responsible for extensive changes in native vegetation throughout the Americas over the past century (Parsons 1972; Williams and Baruch 2000). In the Sonoran Desert of northwestern Mexico (Fig. 1) it has been implicated since the 1950s in the deforestation of hundreds of thousands of hectares (Franklin *et al*. 2006). The severe impacts resulting from this conversion of native rangeland to pasture are followed by subtler, more extensive, ecological changes as buffelgrass invades the surrounding landscape (Yetman and Búrquez 1994; Búrquez-Montijo *et al*. 2002) (Fig. 2). Buffelgrass flourishes in the Sonoran Desert's coarse soils and hot, dry climate (Cox *et al*. 1988; Ibarra-F. *et al*. 1995) through drought tolerance, vegetative reproduction, and prolific seed production (Burgess *et al*.

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Fig. 1 The study area covers 10,687 km^2 of the Sonoran Desert in northwestern Sonora, Mexico. Originally published as Fig. 2 in Brenner, J. C. "Pasture Conversion, Private Ranchers, and the Invasive Exotic Buffelgrass (Pennisetum ciliare) in Mexico's Sonoran Desert." Annals of the Association of American Geographers (forthcoming). Reproduced with permission from Taylor & Francis Group (http://www.informaworld.com)

1991; Van Devender and Dimmitt 2000; Mack 2002) which allow it to outcompete native plants for resources (Lyons *et al*. 2009; Van Devender *et al*. 2009). As buffelgrass expands, dies, and eventually burns, it introduces a self-perpetuating grass-fire cycle that kills native perennials and further favors the establishment of the grass (Brooks *et al*. 2004). This cycle could result in the permanent transformation of the unique and diverse Sonoran Desert into a relatively homogenous exotic savanna (Búrquez-Montijo *et al*. 2002).

The principal human roles in this invasion are the deliberate introduction of buffelgrass through processes of land clearing, tilling, and sowing (hereafter, "pasture conversion") and subsequent pasture management. Previous research examines why ranchers perform pasture conversion (Brenner 2009, 2010). This article addresses how much land is converted to pasture, because the extent and arrangement of pasture has important implications for invasion.

Literature Review

Exotic plant invasion is increasingly addressed in social as well as ecological terms (Robbins 2004; McNeely 2005) as researchers from various disciplines acknowledge the diverse influences of human activities in invasion ecology (D'Antonio *et al*. 1999; Mack and Lonsdale 2001;

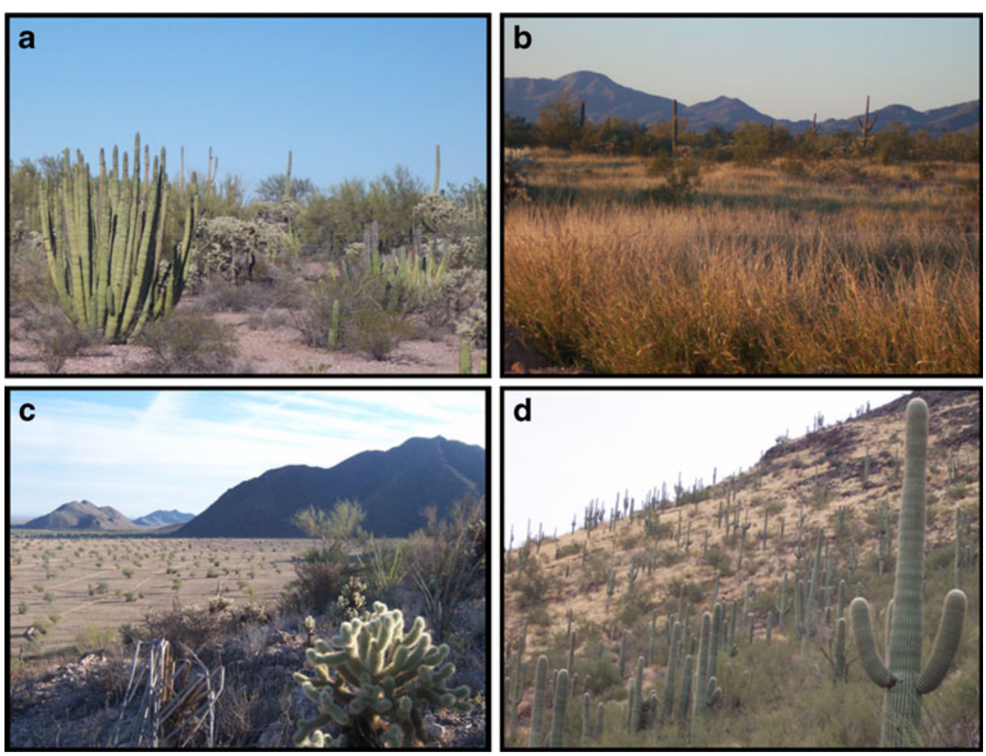

Fig. 2 Diverse Sonoran desertscrub (**a**), composed largely of long-lived perennial cactus and leguminous trees and shrubs, is converted by bulldozer and plow to buffelgrass pasture (**b**), resulting in a savanna-like landscape (**c**, midground) with diminished species richness and compromised ecological function. Buffelgrass then readily invades surrounding landscapes (**d**), outcompeting native species and increasing the risk of wildfire

Perrings *et al*. 2002; Von Der Lippe and Kowarik 2007). One way to make sense of these influences is to characterize social drivers of invasion that operate at different spatial and temporal scales. For example, Henderson and colleagues (2006, 27) consider international commerce and transportation to be direct ("proximate") causes of plant translocation, and population growth, increasing wealth, and trade liberalization as indirect ("ultimate") causes. From this perspective invasion is seen as a product of globalization (Warren 2007; Perrings *et al*. 2010). Other studies are similarly framed in broad economic (McNeely 1999), historical (Crosby 1986), or cultural (Mack and Lonsdale 2001) terms. Because there is considerably less attention to the individuals actually doing exotic plant introduction (for a notable exception, see Head and Muir 2004), important social factors driving biotic invasion remain largely unexamined.

A useful concept for examining the role of individuals in exotic plant introduction and invasion is land use, the realization of productive human activities on a landscape (GLP 2005; Turner *et al*. 2007; Reenberg 2009). Land use encompasses a broad spectrum of human-environment interactions, ranging from intensive management of introduced species (e.g., agriculture) to the preservation of native biota, a task that often requires removal or control of exotics. Indeed, land use and biotic invasion are often linked processes, with land use setting the conditions for biotic invasion, and biotic invasion acting as a driver of land-use change (Hobbs 2000). Human-environment researchers have employed diverse social and ecological data to explain these interactions (e.g., Robbins 2001; Schneider 2006; Schneider and Geoghegan 2006), although their work usually focuses on land use *in response* to invasion—rarely on land use *as a cause* of invasion. An examination of exotic plant introduction and management as a form of land use could thus provide valuable insights about social drivers of invasion.

Meanwhile, an emerging science of land change (Turner *et al*. 2007) considers land-use drivers operating at different spatial and temporal scales (e.g., Lambin *et al*. 2001; Liu *et al*. 2001; Lambin *et al*. 2003; Rindfuss *et al*. 2004). Direct, or proximate, drivers are often understood as the decisions and activities of individual land managers. Indirect, or distal, drivers are the broader social, political, and economic forces that condition those decisions, which originate and largely operate outside the immediate sphere of the land manager (for empirical analysis, see Roy Chowdhury and Turner 2006; for conceptual underpinnings, see Turner *et al*. 2007; and for a comprehensive review, see Turner and Robbins 2008). Direct and indirect drivers operate simultaneously and interact; a complete understanding of land use therefore requires attention to both (Fig. 3). This study examines social variables as direct and indirect drivers of pasture conversion and buffelgrass invasion.

Study Area and Methods

The study area includes 10,687 km^2 of mostly intact Sonoran desert scrub vegetation surrounding Caborca, Sonora, Mexico (Fig. 1) and adjacent to the so-called Central Sonoran Region, an area already well-represented in previous buffelgrass research (Valdez-Zamudio *et al*. 2000; Castellanos *et al*. 2002; Franklin *et al*. 2006). It is located within the Arizona Upland (Brown 1994), a vegetation highly valued for conservation in the United States (Cohn 2001) and extraordinarily susceptible to buffelgrass invasion (Van Devender and Dimmitt 2006) (Fig. 2). The predominant land-use regime in the region since the colonial missionary period of the late seventeenth century is extensive cattle grazing on native rangelands by private ranchers (Perramond 2010; Ibarra-Flores *et al*. 2009). Buffelgrass is increasingly involved in this regime, as time-series analysis of remotely sensed imagery reveals

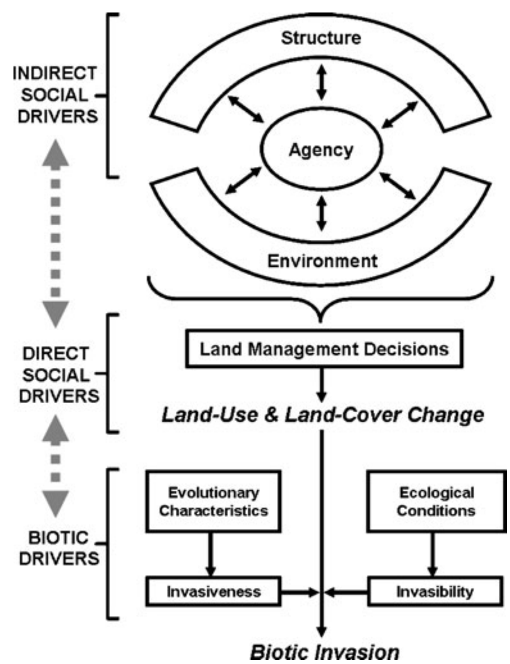

Fig. 3 Integrated framework for understanding interactive drivers of land change and biotic invasion. Land-use decisions are a product of the agency of individual land managers as conditioned by their environment and a broader political-economic, or social, structure. Social drivers (indirect and direct) of biotic invasion emerge from these structure-agency-environment dynamics, and interact in complex ways. Biotic drivers include the intrinsic properties of the invasive exotic species as well as those of the invasible native landscape. Social and biotic drivers also interact (dashed gray arrows) in many ways, some of which are not illustrated here

increasing pasture area from 1973–2006 (Brenner *et al.* unpublished data).

The central research question was what determines the land area a rancher allocates to buffelgrass pasture, so the primary research objective was an understanding of individual land-use decisions. The methods followed a systematic interview scheme described in detail in Brenner (2010). In short, 61 rancher members of the Caborca Local Cattle Association (Table 1) were randomly sampled and interviewed in Spanish using a standardized instrument from June–December, 2007. Interview questions concerned:

(1) duration and size of ranching operations;
(2) physical characteristics and management of ranches;
(3) participation in government-sponsored programs;
(4) environmental perceptions, beliefs, and knowledge;
(5) household socioeconomics; and
(6) knowledge and management of buffelgrass.

A portion of each interview was devoted to open-ended questions that invited elaboration on management practices and strategies, as well as whatever social, cultural, or political matters ranchers deemed noteworthy. Follow-up visits to 14 ranches across the study area lasted up to a day and afforded opportunities to discuss in depth topics such as buffelgrass management, local environmental challenges, and the local socioeconomic and political situation. Visits also allowed observation of pasture conversion patterns and produced a wealth of anecdotal insights that aided the interpretation of interview responses.

Among the 61 interviewees, 40 practice pasture conversion (n=40) and were included in the statistical analysis. An ordinary least squares regression (OLSR) model was used (as in, for example, Lambin *et al.* 2000; Veldkamp and Lambin 2001; Roy Chowdhury and Turner 2006) to ascertain significant determinants of land allocation to pasture. The dependent variable (Y) was total land allocation to buffelgrass pasture (ha). A pool of 166 preliminary independent variables was derived from interview responses, then culled using bivariate OSLR model runs and a significance threshold of $p \leq 0.200$. Eight independent variables were selected for the final OLSR model (Table 2) based on their relevance to the research question at hand and previous research in the region (Brenner 2010). Prior to analysis, base-ten logarithmic transformations were performed on the dependent and the two metric independents to achieve normality; the six remaining independents were coded as categorical binaries (where 1 = yes and 0 = no).

Independent variables in the final OLSR model are the following. Ranching experience (X_1) is the time (yr) spent in ranching as a livelihood. Pasture conversion may arise from expertise gained through experimentation (Pérez López 1992), so pasture allocation should increase with experience. Ranch size (X_2) is the total land area (ha) managed by a rancher. Bigger ranches should have bigger pastures, since land-rich, private ranchers are claimed to be the primary users of buffelgrass (Camou Healy 1998). Rotational grazing (X_3) is a broadly defined management specialization involving herd rotation and intensive grazing on two or more fenced plots (Briske *et al.* 2009, 4 and Table 1). As a significant driver of the initial decision to convert rangeland to pasture (Brenner 2010), rotational grazing hypothetically also promotes larger pasture allocations. Buffelgrass seed harvest (X_4) represents an appreciation of buffelgrass apart from its value as forage. A diversification of benefits from buffelgrass should promote its cultivation. A rancher's belief in buffelgrass as a long-term solution to drought or chronic low productivity (X_5) would hypothetically promote land allocation to pasture. Likewise, a rancher's actual perception of poor forage conditions on the ranch (X_6), should promote larger pasture allocation. Two variables represent ranchers' engagement with government programming, shown elsewhere to strongly favor buffelgrass cultivation (Brenner 2010). Receipt of payments from one or more subsidized ranching assistance programs (X_7) and discovery of buffelgrass through government-sponsored research (X_8) are not significant drivers of the initial pasture conversion decision on local ranches (Brenner 2010), but could hypothetically facilitate large or repeat plantings.

Results

Ranchers at the site, on average, manage 6,667 ha, and convert 942 ha to buffelgrass pasture (Table 2). For every

Table 1 Descriptive statistics of the interview sample (n=61)

	Ranchers		Buffelgrass planters
Interviewees (n)	61		40
Total AGLGC[a] membership		311	
Percentage of AGLGC membership	20%		13%
Total AGLGC ranches		183	
Percentage of AGLGC ranches	33%		22%

[a] *Asociación Ganadera Local General de Caborca* (General Local Cattle Association of Caborca).

Table 2 Summary statistics for variables used in ordinary least squares regression (OLSR) analysis, prior to transformation (n=40)

Variable	Mean	Std. Dev.	Min.	Max.
Y - Absolute land allocation to buffelgrass (ha)	**942**	**2,737**	**10**	**16,800**
Fractional land allocation to buffelgrass (%)[a]	15.0	17.2	0.3	65.1
X_1 - Ranching experience (yr)	26.1	14.2	3	60
X_2 - Ranch size (ha)	6,667	9,466	80	50,000
X_3 - Rotational grazing (binary)	0.875	0.335	0	1
X_4 - Buffelgrass seed harvest (binary)	0.775	0.433	0	1
X_5 - Belief in buffelgrass as a solution to drought or low productivity (binary)	0.750	0.439	0	1
X_6 - Perceived poor range condition (binary)	0.450	0.504	0	1
X_7 - Government ranching assistance (binary)	0.525	0.506	0	1
X_8 - Government research (binary)	0.300	0.464	0	1

[a] Not used in the final OLSR model.

hectare managed, ranchers tend to allocate 0.15 ha (15%) to buffelgrass, although there is great variability in absolute (10–16,800 ha) as well as fractional (<1–65%) land allocation.[1] For instance, the total land area of most ranches was exceeded by the 16,800 ha of pasture allocation on one ranch.

The OLSR model fits the data well and explains much of the variance in land area converted to pasture (R^2=0.679; $p \leq 0.001$) (Table 3). A comparison of standardized regression (β) coefficients shows that the land area ranchers allocate to buffelgrass pasture is determined foremost by ranch size (β=0.600; $p \leq 0.001$) (Table 3). Less powerful, but still significant, are rotational grazing (β=0.301; $p \leq 0.01$) and buffelgrass seed harvest (β=0.296; $p \leq 0.05$) practices. Discovering buffelgrass as a result of government research is also a significant predictor (β=0.238; $p \leq 0.05$) of pasture area. Ranching experience, poor forage conditions, belief in buffelgrass as a long-term drought or productivity solution, and government assistance have insignificant influences on pasture area.

Discussion

The ecology literature on buffelgrass invasion (e.g., Búrquez *et al*. 1996; Van Devender *et al*. 1997; Búrquez-Montijo *et al*. 2002; Búrquez and Martínez-Yrizar 2006; Van Devender and Dimmitt 2006; Morales-Romero and Molina-Freaner 2007) includes minimal, usually speculative, discussion of social dimensions. Meanwhile, a relatively small body of social science illustrates some social consequences of the intensification of Sonoran ranching, and how buffelgrass figures into local conflicts, but offers sparse explanation of the social causes of buffelgrass invasion (Yetman 1996; Yetman and Búrquez 1998; Vásquez-León and Liverman 2004). Results from previous research in the region illustrate social factors driving the decision to do pasture conversion (Brenner 2009; Brenner 2010), and the present study sheds light on how social factors related to land use determine the *extent* of buffelgrass introduction. The results illustrate direct and indirect influences on exotic plant introduction and have implications for invasion.

Ranch Size

The social science literature on ranching in Sonora, Mexico, suggests buffelgrass is more prevalent on big commercial ranches (e.g., Camou Healy 1998: 176; Vásquez-León *et al*. 2003; Vásquez-León and Liverman 2004), and the present study confirms ranch size as the strongest determinant of land area converted to pasture. Although bigger ranchers are not more likely to plant buffelgrass (Brenner 2010), they convert more land to pasture over time, which has relevance to buffelgrass invasion. Furthermore, bigger ranches tend to have pastures spread extensively across multiple parcels, according to microsite variability in native vegetation, topography, soils, and runoff, and existing ranch infrastructure, such as corrals and water systems. Even ranchers with a small total pasture area scatter their plantings as a hedge against pasture failure.

Optimizing the distribution of pastures within a ranch has important implications for buffelgrass invasion. Large ranches in the region tend to occupy flat basins between steep mountain ranges. Almost all ranches have at least one parcel boundary abutting a mountain slope. Ecologically, the most suitable sites for buffelgrass invasion are

[1] All of the ranches in this study (and for that matter at the site) would be considered large in the Sonoran context (Camou Healy 1998). A 50,000-ha land entitlement was not uncommon; one rancher not included in the interview sample reported holdings of more than 200,000 ha, a large fraction of which had been converted to buffelgrass pasture.

Table 3 Ordinary least squares regression (OLSR) model summary (n=40).

Model statistics	Values[a]
F	8.181***
R^2	0.679
Adjusted R^2	0.596
Independent variables	
X_2 - Ranch size (ha)	0.600***
X_3 - Rotational grazing (binary)	0.301**
X_4 - Buffelgrass seed harvest (binary)	0.296*
X_8 - Government research (binary)	0.238*
X_6 - Perceived poor range condition (binary)	0.163
X_5 - Belief in buffelgrass as a solution to drought or low productivity (binary)	0.135
X_1 - Ranching experience (yr)	−0.088
X_7 - Government ranching assistance (binary)	−0.003
Constant	−2.045

[a] Significance: *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$.

the low-elevation alluvial *bajadas* (piedmonts), where buffelgrass escapes damaging frost and benefits from ample runoff and well-drained soils. Lower-elevation bajadas are also ideal for diverse native desert scrub. Forests of ecologically important long-lived succulents and leguminous trees reach their highest density here (Dimmit 2000). This juxtaposition of optimal buffelgrass and native vegetation habitats creates great potential for competition between buffelgrass and native vegetation.

Rotational Grazing

Following ranch size, rotational grazing is the second most important determinant of land area converted to pasture. Ranchers that changed their management scheme from the traditional extensive grazing of open rangelands to the intensive rotational grazing of fenced pastures were more likely to plant large areas in buffelgrass. Intensive grazing requires an increase in forage productivity, and herd rotation requires multiple pastures—both of which are satisfied by increasing land allocation to buffelgrass. Greater pasture area also allows ranchers to more precisely control forage consumption and grazing impacts. An abundance of state-sponsored research in Mexico on rotational grazing systems asserts their ecological and economic benefits, as well as the important role of buffelgrass (Servín *et al*. 1982; Villaseñor *et al*. 1985; Ibarra *et al*. 1987; Ibarra F. 1990; Salcedo Martinez 2007; CIPES n. d.). Although these benefits are contested (Holechek *et al*. 2006; Briske *et al*. 2009), they nevertheless serve locally to rationalize rotational grazing, and they lead to the institutionalization of rotational grazing within government agencies and local cattle associations (Brenner 2010).

The social history of rotational grazing conditions what might seem at first glance a straightforward land management decision made on the ground by individual land managers. Range science principles supporting rotational grazing arose at the turn of the twentieth century in the western United States and were considered universally applicable, so they were exported throughout the developing world (Sayre and Fernández Giménez 2004). Mexico's "livestock as development" policies throughout the 1960s and 1970s (Perramond 2010: 106) were founded on these principles, and in Sonora rotational grazing became a central tenet of the state-sponsored modernization of the region's flagging livestock economy (Pérez López 1991). As Yetman (1996: 107) points out, rotational grazing, buffelgrass pasture conversion, and other forms of "good management" are seen as luxuries feasible only for the wealthiest, so they exacerbate class divides. Perramond (2010) agrees, describing how rotational grazing rhetoric is marshaled by an elite class of private ranchers to assert superiority over smaller, more traditional ranchers. Any analysis of rotational grazing as a driver of social and environmental change must therefore account for its place in the social structure of modern cattle ranching in Mexico—that is, the way rotational grazing was imported from the United States, institutionalized through development policy, promoted by local range scientists, and championed by private ranchers as a symbol of social status. In this light, rotational grazing is clearly part of an oft-cited "political ecology" of Sonoran ranching (Sheridan 1988; Perramond 1999, 2002, 2010; Sheridan 2001), wherein social forces beyond the individual rancher shape day-to-day management decisions. In terms of the present study, the apparently direct role of rotational grazing in determining land allocation to pasture belies an array of related indirect social influences.

Rotational grazing plays multiple roles in promoting the subsequent buffelgrass invasion. As described above, the multiple pastures needed for a rotational grazing system are located adjacent to vulnerable vegetation communities. In addition, rest periods between grazing intervals allow buffelgrass to grow, mature, and produce seeds—processes that are usually retarded by overgrazing on Sonoran rangelands (Chavez 1999; Van Devender and Dimmitt 2006; Nagler *et al*. 2009). Thus, rotational grazing facilitates the spread of buffelgrass not only by fostering its widespread cultivation in dispersed pastures, but also by preventing the overgrazing that might otherwise keep it in check.

Buffelgrass Seed Harvest

Slightly less significant than rotational grazing is the harvest of buffelgrass seed from established pastures. Some ranchers find value in buffelgrass beyond its utility as forage, with the clearest example being the commercial production of buffelgrass seed—a small, but significant, industry in Sonora (Yetman 1996:106). Even short pasture rest intervals enable seed production since buffelgrass can set seed in a matter of weeks (Ward *et al*. 2006). Many ranchers find it economically justifiable to set aside a portion of their pastures for seed production, and some make considerable investments in land, labor, and machinery for this purpose. A few are regionally renowned for producing abundant, high-quality buffelgrass seed. Ranchers also harvest and sow buffelgrass seed on their own lands. Seed collection on ranches can reduce reliance on expensive commercial seed and sustain pasture conversion over a longer term. Seed prices that had remained consistently low throughout the 1990s and early 2000s (at around US$3/kg) have nearly doubled in recent years, making the total cost per hectare approximately US$87 in 2008 (Navarro-Navarro 2008). Recent price increases thus make seed harvest increasingly important.[2] Unlike rotational grazing, which has a strong socio-structural base, seed harvest appears to have arisen among ranchers through experience and experimentation, and in this way it is a direct driver of large land allocation to buffelgrass. At the same time, however, pasture conversion and management decisions are indirectly driven by changes in the buffelgrass seed market.

Seed production promotes invasion in two ways. First, the pasture rest intervals involved in rotational grazing allow buffelgrass propagules to escape from pastures and colonize outlying lands. Second, harvested seed is intentionally sown by some ranchers on intact native rangelands (in addition to cleared and tilled pastures), especially on vulnerable slopes. The northern European cattle now predominant in the region tend not to graze these slopes, so ranchers will not convert these areas to pasture. However, ranchers will sow these ungrazeable areas to attract wildlife, such as whitetail deer (*Odocoileus virginianus*), mule deer (*O. hemionus*), desert bighorn sheep (*Ovis canadensis nelsoni*), and Sonoran pronghorn antelope (*Antilocarpa americana sonoriensis*). These trophy species attract lucrative sport hunting contracts that can deliver more income than feeder calf production. This managed invasion on intact wildlands transforms previously useless areas into valuable income-generating property, allowing ranchers to diversify livelihoods while holding onto traditional lands and lifestyles. As ranchers here and elsewhere (see Archer 2004) turn to sport hunting in times of climatic and economic uncertainty, the local practice of managed buffelgrass invasion will likely continue.

Government Research

Previous research shows that less than one third of buffelgrass planters discovered buffelgrass through government research and extension (Brenner 2010). This study shows, however, that those ranchers allocate disproportionately large areas to pasture, and that government research is therefore a significant driver of pasture conversion (Table 3).

Several ranchers with extensive pastures remark that they discovered buffelgrass in dense pastures beside the highway leading to Sonora's capital, Hermosillo, then sought more information about buffelgrass among peers in Caborca. These high-profile pastures are planted at the Carbó Experimental Station, created in the 1960s as part of a boom in state and federal range-science research (SPP 1985; Salcedo Martinez 2007), which in turn was part of a broader economic development program funded by multilateral development banks (Sanderson 1986; Camou Healy 1998; Perramond 2010). Although the numerous publications produced by this research, which tout buffelgrass as a miracle for Sonora's rangelands (e.g., COTECOCA 1968; Johnson-G and Aguayo-A 1973; Martín-R 1990; CIPES n. d.), are either lost on or ignored by Caborca's ranchers (Brenner 2010), the plots where the research took place are not. In an indirect way, then, government research promotes the conversion of extensive areas to pasture by exposing a few Sonoran ranchers to buffelgrass and initiating a diffusion of awareness throughout the ranching community. This is consistent with Rogers's (2003:16) principle of "observability" in diffusion theory, which holds that "the easier it is for individuals to see the results of an innovation, the more likely they are to adopt." Early adopters then inspire curiosity and promote awareness among peers. Experimentation ensues, eventually producing the requisite knowledge for large-scale pasture conversion.

[2] Seed still represents a relatively small fraction of the total cost of pasture conversion (9–25% by official figures), so it is unlikely that even drastic increases in seed costs would prevent a rancher from planting buffelgrass.

Conclusions

This study focuses on land management changes predominant in northwestern Mexico since the 1950s and examines the influence of some of these changes on the introduction and invasion of buffelgrass. It shows ranch size as the most important determinant of total pasture area, with the relatively few ranchers who control the largest expanses of land at the site being the most likely to convert large areas to pasture. This result has both troubling and promising implications for controlling buffelgrass invasion in the region. On one hand, a few land managers can introduce extensive sources of buffelgrass propagules adjacent to vulnerable landscapes and have a widespread and profound effect on region-wide buffelgrass invasion. For example, a single rancher with 25,800 ha of land converted 65% of it (16,800 ha) to buffelgrass. On the other hand, if a few large ranchers ceased to use buffelgrass, it could produce a similarly widespread ecological benefit. Other forage species, for example, Johnsongrass (*Sorghum halepense*), rye grass (*Lolium perenne* L.), or Kleingrass (*Panicum coloratum* L.) perform similar functions on rangelands but are less invasive than buffelgrass.

The buffelgrass case illustrates how the interactions of direct and indirect social drivers create complex dynamics that perpetuate extensive exotic plant introduction and ultimately foster invasion. Beyond simply confirming that introduction and invasion are complex processes, this study explains how and why. Three examples illustrate. First, region-wide pasture conversion creates demand for buffelgrass seed, which promotes the creation of new pastures and the intensive management of existing pastures. Second, the pasture rest intervals that are part of a novel grazing scheme also enable buffelgrass seed harvest, which further promotes pasture expansion. Third, widely dispersed pastures, managed through rotational grazing at various degrees of exploitation, allow buffelgrass seed set and dispersal throughout surrounding landscapes.

This study suggests that invasive species policy consider the direct role of day-to-day land management in exotic species introduction and invasion, as well as indirect roles played by agricultural markets, economic development initiatives, and agronomic research agendas. Furthermore, direct and indirect social drivers may interact to influence biotic invasion in unanticipated ways. Perhaps economic development incentives for traditional ranching alongside other ecologically sustainable livelihoods (e.g., sport hunting on native rangeland) could reduce the rate of pasture conversion and the extent of buffelgrass invasion in the region (Brenner 2010). In the meantime, however, as Yetman (1996:106) points out, "buffelgrass is very, very popular," and this popularity, alongside a 50-year legacy of governmental sponsorship, stands as a formidable barrier to change.

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