BUYING TIME:

# A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems

## CHAPTER 1: Grasslands

*editors*
L.J. Hansen,
J.L. Biringer,
and J.R. Hoffman

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# Grasslands at a Crossroads: Protecting and Enhancing Resilience to Climate Change

*Jonathan L. Gelbard, Ph.D.*
*Department of Environmental Science and Policy, University of California, Davis*

**THE STRUCTURE AND FUNCTION OF** the world's grasslands makes them one of the most vulnerable to global climate change of any terrestrial ecosystem (Sala et al., 2000; IPCC, 2001a). The low-stature of vegetation confers high light availability, leaving many grasslands naturally vulnerable to invasive species (Wagner, 1989), especially following disturbance (Hobbs and Huenneke, 1992). A critical role for fire in maintaining plant community structure in many grassland types leaves them vulnerable to vegetation change should changes to temperatures and precipitation occur that are sufficient to alter biomass and fire frequency. Grasslands are also vulnerable due to human environmental impacts, including conversion to agriculture (both cropland and grazing land) (Dale et al., 2000; Ricketts and Dinerstein, 2001), the introductions and spread of invasive species (Mack et al., 2000; Mooney and Hobbs, 2000), the proliferation of roads (Forman and Alexander, 1998; Forman, 2000), alterations to fire regimes (D'Antonio, 2000; Dale et al. 2000), and pollution that alters soil fertility and rates of plant growth (Schlesinger, 1997; Lejeune and Seastedt, 2001). Combine the above natural and anthropogenic vulnerabilities, and it is apparent that when faced with human-induced global climate change (Schlesinger, 1997; IPCC, 2001b), what remains of the world's grassland ecosystems as we know them are in trouble (Forseth, 1997).

Fortunately, however, the fate of grassland ecosystems faced with climate change, which has the potential to favor different groups of species and alter ecosystem processes, is not yet sealed. Although in some regions, habitats are far more degraded and in need of restoration and recovery than others (see Ricketts and Dinerstein, 2001 and the World Wildlife Fund's Ecoregions website, *http://www.worldwildlife.org/ecoregions/index.htm,* for an overview of the world's grassland types and assessment of their conservation status), scientists, land managers, and policymakers, with the help of private landowners, still have time to devise and implement adaptations that will be needed to protect and conserve grasslands from threats posed by global climate change. This chapter summarizes current scientific knowledge concerning potential steps that will be required to achieve this goal.

It first outlines the components of grassland ecosystems that will prove crucial to their resilience to climate change and describes human environmental impacts to them. Resilience is defined as the ability to withstand not only possible episodic climate changes, but also possible long-term directional changes (Malcolm and Markham, 1996); it may vary depending on the ecosystem component in question (Lavorel, 1999). The chapter then outlines potential impacts of predicted climate changes on grasslands given their current human-altered environmental condition. Finally, it proposes adaptations that may prove useful for preventing or minimizing these effects, and discusses complex challenges that could arise during translation of proposed strategies into the management plans and policies that will be required to maintain and restore grassland resilience.

## Crucial Components of Grassland Ecosystems

The condition of vegetation and soils will prove critical to grassland resilience to climate change. Healthy, vigorous stands of native vegetation are likely to be more resilient to warming temperatures and increasing frequency and duration of droughts than degraded grasslands because their roots have access to deeper soil moisture and they are better able to compete with invasive species (Goodwin et al., 1999; Enloe et al., 2000; Stohlgren et al., 2001; Gelbard, 2003). Healthy plant cover is critical for intercepting rainfall, maximizing infiltration and soil water supply, reducing overland flow, and preventing nutrient losses due to erosion (Noss and Cooperrider, 1994). A healthy level of soil organic matter is important for soil aggregate formation, fertility, stability, water movement and holding capacity, and aeration, and therefore influences plant growth. Plant growth and vigor is largely determined by physical, biotic, and disturbance factors that limit primary productivity, including water availability (Sala et al., 1988), nutrient cycling (West, 1983; Schlesinger, 1997; Evans and Belnap, 1999), the suite of competing species (Grace and Tilman, 1990), healthy soil biota (Allen et al., 1992; Belnap and Lange, 2001), and the native disturbance regime (e.g., herbivory, fire; Mack and Thompsen, 1982; Collins, 1992; D’Antonio, 2000). Soil water-holding capacity and precipitation patterns are the major determinants of water availability for plants (Jenny, 1980), which in turn is the major determinant of plant growth (Schlesinger, 1997).

Abundance and relative composition of plant species are increasingly recognized to depend on various ecological processes such as herbivory and fire (Soule and Terbourgh, 1999; Ricketts and Dinerstein, 2001). Changes to the above ecosystem components due to climate change, human environmental impacts, or synergisms therein have the potential to influence grassland composition and/or function, and therefore resilience (Mack, 1989; Forseth, 1997; Mooney and Hobbs, 2000). The status of these ecosystem components differs among grasslands (Carpenter, 2001; Dellafiore, 2001; Ricketts and Dinerstein, 2001; Seymour and Rowan, 2001), depending on such factors as the degree to which their native species and soil biota are adapted to the current disturbance regime (Mack, 1989; Milchunas and Lauenroth, 1993).

## Stresses and Vulnerabilities Due to Factors *Other* Than Climate Change

Numerous human disturbances and stresses are causing substantial degradation to the crucial components of grassland ecosystems outlined above (Walker, 1995). These include habitat fragmentation and loss, the spread of invasive species, alteration of fire regimes, and pollution; and all may act alone or synnergistically, leaving grasslands particularly vulnerable to climate change (Walker and Steffen, 1997; Dale et al., 2000).

### HABITAT FRAGMENTATION AND LOSS

Throughout the world, grasslands have been degraded by livestock grazing, converted to agriculture and urban centers, and fragmented by roads (Dale et al., 2000).

*LIVESTOCK GRAZING:* Livestock grazing is undoubtedly the major land use of the world's remaining grasslands (IPCC, 2001a), and it is listed as a threat to these systems on all continents except for Antarctica (Richardson et al., 2000; Carpenter, 2001; Dellafiore, 2001; Dinerstein and Louks, 2001; Hobbs, 2001; Ricketts and Dinerstein, 2001). Its impacts are variable depending not only on the intensity, timing, duration, and type of grazing animal, but on environmental conditions and the ecosystem and plant life form in question (Mack, 1989; Noy-Meir et al., 1989; Milchunas and Lauenroth, 1993; Harrison et al., 2003). Livestock grazing diminishes grassland resilience by compacting soils, thus reducing infiltration and soil water capacity and drying out surface soils, which may increase vulnerability to drought and accelerate desertification (Schlesinger et al., 1990; Robertson, 1996, Fig. 1). It causes substantial degradation to riparian habitats (Belsky et al., 1999), which are hot spots of native biodiversity within grasslands, and provide connectivity between grassland patches (Noss and Cooperrider, 1994; Stohlgren et al., 1998). Livestock cause erosion and topsoil loss and destroy biological soil crusts (living crusts composed of lichens, mosses, algae, and cyanobacteria that cover the soil surface between individual grasses, shrubs, and trees in many semi-arid grasslands, and that are critical for maintaining soil fertility and plant vigor; Belnap and Lange, 2001) that may result in considerable nutrient losses (Archer and Smeins, 1991; Evans and Belnap, 1999; Belnap and Lange, 2001). They also cause localized increases in soil fertility where they concentrate, such as near water sources and under trees (Dalhgren et al., 1997; Belsky and Gelbard, 2000). Vegetation within such nutrient hot spots tends to be dominated by invasive species, and these sites may act as foci for further invasion (Belsky and Gelbard, 2000). The result of changes to soil fertility and structure caused by livestock, combined with seed introductions of invasive species and selective grazing of palatable species over weedy ones frequently results in reductions in both the vigor and reproduction of native species and an acceleration of the spread of invasives (Buffington and Herbel, 1964; Schlesinger et al., 1990; Archer et al., 1995; Belsky and Gelbard, 2000; Hobbs, 2001; IPCC, 2001a). These impacts leave grasslands highly vulnerable to climate changes that may favor invasive species (Baskin, 1998).

Fig. 1. Intensive sheep grazing favors exotic annuals such as *Erodium cicutarium* in Carrizo Plain National Monument (Fig. 1a; photo by J. Gelbard) and by causing terracing that compacts soils, reducing infiltration and increasing overland flow and topsoil loss (Fig. 1b; photo by J. Gelbard).

**Figure 1a.**

**Figure 1b.**

*CONVERSION TO AGRICULTURE:* Vast expanses of grassland habitat have been converted to agriculture, whose spread has often left remaining patches surrounded within a sea of crop fields, irrigated pastures, vineyards, and orchards (Noss and Cooperrider, 1994, Dale et al., 2000, Ricketts and Dinerstein, 2001). Grasslands from the Argentine Pampas (Dellafiore, 2001), to the Kazakh steppe (Ponomarenko, 2001), to the American tallgrass and Palouse prairies (Ricketts and Dinerstein, 2001), have been almost entirely converted to agricultural production, leaving few intact habitats remaining. Such isolation leaves grassland species little room to migrate in response to climatic changes. Agricultural impacts to grasslands stretch beyond habitat fragmentation and loss. For example, due to changes in the level of surface water evaporation, irrigated agriculture may alter regional climate in such a way as to influence plant community composition (Baron et al., 1998).

An impact to grasslands that often accompanies agricultural conversion is pesticide use. The application of toxic pesticides may poison soils, alter below-ground communities, weaken native plants, and lead to the loss of native species or invasions of different types of exotics (Frenkel, 1970; Myers and Kent, 1996; Tyser et al., 1998; Dale et al., 2000). Even supposedly weed-specific herbicides such as Clopyrid (Transline), which is used to control yellow starthistle *(Centaurea solstitialis)*, may lead to the loss of functional groups such as asters and legumes (DiTomaso et al., 2000), potentially reducing nitrogen availability and destabilizing plant community composition.

*PROLIFERATION OF ROADS:* Roads are the entry points for virtually all human environmental impacts to grasslands, including conversion to agriculture and subdivisions, livestock grazing, off-road vehicle (ORV) use, arson fires, and the spread of invasive species (Forman and Alexander, 1998). Of particular concern for grassland resilience, roads are the pathways by which invasive plants are spread away from ports and other original points of introduction and throughout a geographic region (Frenkel, 1970; Belsky and Gelbard, 2000; Gelbard and Belnap, 2003). For example, seeds of 124 plant species, a high proportion of which were exotic, were collected from an automobile as it was driven more than 15,000 km throughout Central Europe (Schmidt, 1989). In Australia, researchers collecting seeds from vehicles in Kakadu National Park found 14 exotic species not known to be present in the area (Lonsdale and Lane, 1994). Whether in Africa (Milton and Dean, 1998), the Middle East (Holzapfel and Schmidt, 1990), Europe (Schmidt, 1989), the United States (Gelbard and Belnap, 2003), or Australia (Lonsdale and Lane, 1994), this typically results in roadsides being highly invaded habitats. In Serengeti National Park, for example, road shoulders contained ruderal species that did not occur in naturally disturbed or climax communities (Belsky, 1987). In the western United States, the noxious weed, yellow starthistle occurred in 73% of quadrats 10 meters from roads, but only 21% of quadrats greater than 1000 m from roads (Gelbard and Harrison, 2003). Roadsides in the Middle East were dominated by Mediterranean species, while adjacent habitats were dominated by Saraho-Arabian species (Holzapfel and Schmidt, 1990).

**Figure 2. Off-road vehicle (ORV) damage to plants and soils in a rare serpentine grassland.**

Photo by J. Gelbard.

The construction and improvement of roads can be considered an important agent of land cover change. Gelbard and Belnap (2003) estimated that construction of 10 kilometers of paved roads converts as much as 12 hectares of natural habitat to highly invaded roadside habitats that can act as conduits for the spread of invasive species. Conversely, roadless habitats are often refuges for native species (Soule and Terbourgh, 1999), but such habitats are typically rare at the landscape scale. In an area of northern California, for example, grasslands greater than 1000 meters from roads composed only 1.5% of the landscape (Gelbard and Harrison, 2003). This study provided a striking illustration of how the expansion of a road network fragments and degrades grasslands, leaving them highly vulnerable to additional vegetation changes induced by climatic shifts.

An impact to grasslands that is directly related to roads is off-road vehicle (ORV) use, which damages vegetation and soils and spreads invasive plant seeds (Fig. 2; Webb and Wilshire, 1983; Noss and Cooperrider, 1994). Inadequate attention in management plans and insufficient enforcement of existing regulations have resulted in hundreds of thousands of kilometers of unauthorized ORV routes across grassland landscapes.

*URBANIZATION:* Throughout many areas of the world, grasslands occupy valley bottoms and other habitats of low topographic position, which are the most accessible for development (West, 1983). As a result, they have been especially vulnerable to habitat loss due to urbanization (Gerlach et al., 1998; Fig. 3).

**Figure 3. Untold extents of grassland habitat have been lost to urbanization.**

Photo by J. Gelbard.

## SPREAD OF INVASIVE SPECIES

The introduction and spread of exotic and otherwise invasive plant species *(exotic* species are not native to an ecosystem, while *invasive* species are those that spread rapidly from original points of introduction) poses a considerable threat to many of the world's remaining grasslands. Invasive species possess traits that make them highly adaptive to climate change, including tolerance of a wide range of environmental conditions, resistance to human disturbances, and rapid rates of growth, seed production, and dispersal (Baskin, 1998; Dukes and Mooney, 1999; IPCC, 2001a). They include not only plants, but also pathogens such as barley yellow dwarf virus, which afflicts some native bunchgrass species and may act in conjunction with moisture stress caused by competition with exotic annuals to contribute to high bunchgrass seedling mortality (Malmstrom, 1998). Impacts of invasive species include species endangerment (Wilcove et al., 1998), reductions in biodiversity (Rosentreter, 1994) and wildlife habitat (Bedunah, 1992), alterations to ecosystem processes such as fire frequency (D'Antonio and Vitousek, 1992), and nutrient cycling and hydrology (Vitousek et al., 1997), increases in topsoil loss (Lacey et al., 1989), alterations to soil microclimate (Evans and Young, 1984), and reductions in land value and livestock forage capacity (Sheley and Petroff, 1999; Naylor, 2000). The most severe impacts of invasive species often occur where they alter the disturbance regime (D'Antonio, 2000; Levine et al., 2003). The invasive species problem can often be considered a subset of many of the human impacts described in this section (Archer et al., 1995; Knops et al., 1995; Belsky and Gelbard, 2000).

### ALTERED FIRE REGIMES

Humans have caused dramatic alterations to grassland fire regimes (D'Antonio, 2000), which are often important determinants of plant community composition (Collins, 1992; Ricketts and Dinerstein, 2001; Keeley, 2001). In some grassland types, such as the Intermountain West, USA, shortening of the fire return interval due to invasions has favored fire-tolerant plant species, resulting in the loss of fire-intolerant bunchgrasses, shrubs, and associated wildlife (D'Antonio and Vitousek, 1992; Knick and Rotenberry, 1997; D'Antonio, 2000). Other impacts of increased fire frequency include accelerated nutrient losses through volatilization and mortality of biological crust organisms (Schlesinger, 1997; Belnap and Lange, 2001), and losses of rare species (Rosentreter, 1994). Fuel breaks created to suppress fire may further alter grasslands by acting as conduits for the spread of invasive species into uninfested habitats (Keeley, 2001). The area impacted by increased fire frequency may expand with climate change, and thus this threat can also be considered a potential climate change impact (Current and Future Stress, pg.39).

In other grasslands, human-caused decreases in fire frequency have negatively influenced ecosystem health, especially where dominant native species are more fire tolerant than invaders (e.g., Collins, 1992; Heady, 1995; Dale et al., 2000). In California grasslands, for example, low intensity fire can favor native bunchgrasses such as *Nassella pulchra* (Heady, 1995; DiTomaso et al., 1999; Keeley, 2001), while fire suppression results in the build-up of a thick layer of exotic annual grass thatch that hinders the establishment and reproduction of many native species (Menke, 1989; Heady, 1995).

### POLLUTION

*INCREASED ATMOSPHERIC $CO_2$:* The rise in atmospheric $CO_2$ concentrations caused by human activities (Schlesinger, 1997) may have variable effects on grasslands, depending on environmental conditions such as soil fertility, climate, and the species mix

(Forseth, 1997; Dukes and Mooney, 1999; IPCC, 2001a). One effect of increased $CO_2$ concentrations is increased water use efficiency of plants, because the amount of time that they need to leave stomata open for $CO_2$ uptake is reduced (Forseth, 1997; Schlesinger, 1997). Experiments have shown that as a result, heightened $CO_2$ levels increase soil moisture, which may negatively impact grasslands where such conditions favor invasive species (Hobbs and Mooney, 1989; Dukes and Mooney, 1999; Dukes, 2000).

The effect of increased $CO_2$ on grasslands may also depend on the mix of C3 vs. C4 species in a community. Plants with the C3 photosynthetic pathway such as many bunchgrasses (e.g., *Stipa* spp.) and mesquite *(Prosopis* spp.) may increase photosynthetic rates up to concentrations of 1000 parts per million $CO_2$ and beyond (Pearcy and Ehleringer, 1983), and therefore may show enhanced growth rates as $CO_2$ concentrations increase. In contrast, plants with the C4 photosynthetic pathway, such as many *Bouteloua* species of the Great Plains, USA, are already saturated by $CO_2$ at current atmospheric levels and are expected to show little if any increase in growth with rising $CO_2$ levels (Woodward et al., 1991; Forseth, 1997). The result may be to favor C3 over C4 species, though the likelihood that this will occur remains uncertain (Walker and Steffen, 1997), and may depend on environmental conditions such as moisture availability (Forseth, 1997) and the current disturbance regime (Mack and Thompsen, 1982; Milchunas and Lauenroth, 1993). Since rising temperatures may increase terrestrial $CO_2$ outputs into the atmosphere by increasing decomposition rates, especially in northern latitudes where soils contain substantial carbon stores (Schlesinger, 1997), effects of rising $CO_2$ levels on grasslands may be augmented by climate change (Current and Future Stress, below).

*NITROGEN DEPOSITION:* Doubling of nitrogen (N) inputs into the terrestrial N cycle as a result of human activities is leading to accelerated losses of biological diversity among plants adapted to efficient use of N and animals and microorganisms that depend on them (Vitousek et al., 1997). Increased N availability degrades grasslands by favoring weedy species and reducing native species richness (Huenneke et al., 1990; Wedin and Tilman, 1996; Schlesinger, 1997, Weiss, 1999; Scherer-Lorenzen et al., 2000; Lejeune and Seastedt, 2001), especially in habitats characterized by higher temperatures and precipitation (Walker and Steffen, 1997). For example, Lejeune and Seastedt (2001) concluded that N deposition has been an important contributor to the spread of knapweeds *(Centaurea* species). Experimental studies have shown N addition to result in losses of species diversity in grasslands (Huenneke et al., 1990; Wedin and Tilman, 1996), especially when combined with disturbance (Hobbs, 1989), including by resulting in losses to mycorrhizal species that are important to native persistence (Egerton-Warburton and Allen, 2000). Effects of climate change on grassland community composition may be especially pronounced in grasslands impacted by N deposition (Zavaleeta et al., 2003).

*CFCS AND STRATOSPHERIC OZONE DEPLETION:* The loss of stratospheric ozone ($O_3$) due to human activities has resulted in increased UV-B radiation at the Earth's surface (Schlesinger, 1997). Plant response to UV-B radiation spans from little effect to large reductions in photosynthesis and growth, depending on environmental conditions (Forseth, 1997), but may result in changes in competitive balance in terrestrial plant communities (Barnes et al., 1988).

*OTHER POLLUTANTS:* Pollutants such as tropospheric ozone ($O_3$), which is phytotoxic, and sulfur and nitrogen oxides (SOx, NOx), which combine with rainwater to form acid rain, may weaken native species, reducing their ability to withstand some of the above stresses (Schlesinger 1997, Walker and Steffen, 1997). In more mesic grasslands where acid deposition results in losses of basic cations via leaching (Schlesinger, 1997), it may result in nutrient limitations that weaken native plants, increasing their vulnerability to stress induced by drought, disease, and competition with invasive species, and therefore to climate change.

## Current and Future Stress and Vulnerability Due to Climate Change

### PROJECTED CLIMATE CHANGES TO GRASSLAND ECOSYSTEMS

General circulation models (GCMs) predict grassland ecosystems to experience climatic changes including higher maximum (daytime) and minimum (nighttime) temperatures, and more intense precipitation events (IPCC, 2001b). They predict precipitation to increase over northern mid-high latitude grasslands with larger year-to-year variation, including increased frequency of droughts and floods associated with El Niño events, and project both regional increases and decreases for low latitudes (IPCC, 2001b). Within each grassland type, the nature and degree of impacts caused by climate changes is likely to depend on both environmental conditions and individual species or plant life form, due to differences in competitive abilities, migration rates, and responses to disturbance (Forseth, 1997; Dukes and Mooney, 1999; Malcolm and Pitelka, 2000; Buckland et al., 2001; Zavaleta et al., 2003). Location of sites within a grassland region may also be important, as ecotonal habitats are most likely to experience vegetation changes (Neilson, 1993). The degree to which human-caused disturbances and stresses (Stresses and vulnerabilities, pg.33) have already degraded resilience is also likely to prove critical to the future response (Forseth, 1997; Malcolm and Markham, 1996; Schlesinger, 1997). Unlike past climatic changes, the current suite of species in most grasslands often includes species intentionally and accidentally introduced from all over the world, leaving considerably greater potential for climatic shifts to cause or accelerate large-scale vegetation change (Mack, 1989; Mooney and Hobbs, 2000).

### POTENTIAL IMPACTS OF INCREASED PRECIPITATION

In grasslands predicted to experience an increase in precipitation (IPPC, 2001b), such as those of the western United States, this may alleviate moisture stress resulting from rising temperatures. However, it may also accelerate nutrient cycling (e.g., N mineralization), increasing both productivity (Breymeyer et al., 1996) and the germination, seedling survival, and spread of many invasive species (Hobbs and Mooney, 1989; Baskin, 1998; Dukes and Mooney, 1999; Sutherst, 2000). In hot desert grasslands (e.g., within Australia, the Sonoran and Chihuahuan deserts of Mexico and the USA), GCMs predict an increase in the frequency of intense precipitation events and flash floods. This climatic prediction, combined with the likelihood that rising temperatures will increase oxidation of soil organic matter important to soil stability (Walker and Steffen, 1997), is likely to increase erosion and nutrient loss, especially in already-disturbed habitats. If such climatic changes are accompanied by a decrease in less-intense precipitation events, grasslands may experience a net loss in water availability, since in more arid systems, much of the water that falls in the form of intense events often runs through the system and is not absorbed.

### POTENTIAL IMPACTS OF DECREASED PRECIPITATION

Other grasslands, including continental interiors such as the Canadian Prairie, Central Australia, the African Serengeti, and the Great Plains, USA, are expected to experience a *decrease* in precipitation (IPCC, 2001b). Possible consequences include decreased productivity and water availability and increased risk of wildfire (Baron et al., 1998; IPCC, 2001a), which may result in losses of rare species and soil biota, disruption of N cycling, and associated impacts to grassland flora and fauna (Knick and Rotenberry, 1997; D'Antonio, 2000; Belnap and Lange, 2001). Since biological soil crusts may act as a physical barrier to the establishment of some invasive species (Mack, 1989), large-scale reductions in crust cover due to increased frequency of drought and fire may accelerate the spread of exotic annuals such as cheatgrass *(Bromus tectorum)* (Stohlgren et al., 2001; Gelbard and Belnap, 2003). In other grassland habitats, however, including in northern Europe (Buckland, et al. 2001), South Africa (Richardson et al., 2000), and California (Hobbs and Mooney, 1989), an increase in the frequency and duration of drought may cause declines in the abundance of some exotic species, allowing for the recovery of some natives.

### POSSIBLE SYNERGISMS AMONG CLIMATE CHANGES AND HUMAN ENVIRONMENTAL IMPACTS

Synergisms among climate change and other human impacts, such as among grazing, ORV use and increased frequency of drought, may also negatively impact grasslands. For example, effects of drought on vegetation are likely to be more severe where trampling disturbances have reduced infiltration and soil water capacity (Schlesinger et al., 1990; Baron et al., 1998). As noted above, warming temperatures and higher precipitation may increase biomass and therefore fire frequency and intensity, especially where grasslands are dominated by summer-dry exotic annuals (D'Antonio, 2000). One result may be a feedback in which increased fire frequency results in the displacement of native bunchgrasses and shrubs, opening still more habitat to invasion (D'Antonio and Vitousek, 1992). In other possible synergisms, the probability that increased precipitation and $CO_2$ concentrations (which are likely to further increase with climatic warming due to oxidation of soil carbon stores, especially in northern latitudes; Schlesinger, 1997) will alter plant community composition is likely to be highest in areas subjected to high nitrogen deposition (Dukes and Mooney, 1999; Sala et al., 2000, Zavaleta et al., 2003), while an increase in the frequency of drought may have particularly severe consequences for rare species (Tilman and El-Haddi, 1992), especially in the presence of human impacts to vegetation and soils described above. Of course, one never knows what surprises Mother Nature may spring upon grasslands in the future (Malcolm and Markham, 1996; Schneider and Root, 1996; Broeker, 1997), as potential climate changes and their consequences remain difficult, if not impossible, to predict with a high degree of certainty (Walker and Steffen, 1997).

## Adaptation Options

Many possible strategies (adaptations) may prove useful for maintaining and restoring the resilience of grassland ecosystems to climate change.

*Represent grassland types across environmental gradients in protected areas:* Because we do not know precisely which grassland types will be most sensitive to climate change, maintaining all types in replicated protected areas across environmental gradients (to protect against the loss of individual reserves to catastrophic events), with management appropriate to the native disturbance regime, will help to ensure that resilient types persist (Noss and Cooperrider, 1994; Soule and Terbourgh, 1999; Dale et al., 2000). Reserve systems should include heterogeneous topographic, soil, and management conditions to maintain full suites of native species (Noss and Cooperrider, 1994; Markham and Malcolm, 1996; Halpin, 1997; Soule and Terbourgh, 1999, Fuhlendorf and Engle, 2001). They should also be designed to protect rare species and recognize where isolation may hinder their ability to migrate as the climate changes (Markham and Malcom, 1996)

*Protect relict and native-dominated communities as appropriate per system:* Maintenance of relict grasslands (Driscol, 1964; Mason et al., 1967; Jeffries and Klopatek, 1987; Ambos et al., 2000) is crucial because these communities both serve as models for habitat restoration and help us to understand how grasslands altered versus unaltered by human activity are affected by climate change. Since many relict communities are isolated in remote sites surrounded by altered habitats, they could prove vulnerable to climatic shifts (Halpin, 1997). Isolation may also have beneficial effects, however, such as by protecting relict communities from the introduction of exotic plant seeds and diseases that afflict native species (Gelbard, 2003).

*Minimize fragmentation by land use changes and roads:* The negative effects of ecosystem fragmentation are abundantly documented worldwide (Noss and Cooperrider, 1994; Soule and Terbourgh, 1999; Dale et al., 2000). Core grassland habitats distant from roads and human disturbances are often refuges for native species, but roads are so widespread that such habitats are typically rare at the landscape scale (Gelbard and Harrison, 2003). Conversely, fragmentation of grassland ecosystems by roads and land use changes contributes to reductions in native biodiversity, both by eliminating grassland habitats entirely and by facilitating the spread of invasive species (Forman and Alexander, 1998; Gerlach et al., 1998; Gelbard and Belnap, 2003). Activities that fragment grasslands should be minimized, while roadless and otherwise relatively intact core habitats should receive some form of protection (Noss and Cooperrider, 1994; Dale et al., 2000).

*Connectivity is the antithesis of fragmentation.* Corridors or stepping-stones of suitable habitat may facilitate the migration of species in response to climate change, and are important for maintaining species migrations and gene flow (Noss and Cooperrider, 1994; Dale et al., 2000). However, connectivity can also be detrimental where it provides a conduit for the spread of invasive species and diseases that afflict native species (Markham and Malcolm, 1996). In grassland ecosystems, connectivity should be considered where it is critical for maintaining gene flow among populations of rare species and in avoiding fragmentation (Noss and Cooperrider, 1994). Maintenance of intact riparian habitats—often hotspots of biological diversity in grasslands—is one approach for retaining connectivity among grassland patches (Noss and Cooperrider, 1994).

*Practice low-intensity, sustainable grazing practices:* Proper livestock management is critical for maintaining grassland components crucial to resilience. Grazing should be maintained in grasslands where native species are adapted to it (Baker, 1978; Mack, 1989), while land managers should consider reducing or removing grazing from marginal lands (e.g., semi-desert and desert grasslands) and systems where the predominant native species lack a long evolutionary history of grazing by large hooved herbivores (Mack, 1989; Milchunas and Lauenroth, 1993). Invaded or otherwise degraded grasslands are likely to pose more complex management challenges (Billings, 1990; Archer and Smeins, 1991; Brenton and Klinger, 1994), and may require active restoration. Within grazed grasslands, it is important to maintain heterogeneity of management at the landscape-scale and mimic grazing patterns of native herbivores to maximize native biodiversity (Noss and Cooperrider, 1994; Fuhlendorf and Engel, 2001). Such measures are likely to help promote the resilience of grasslands to climate change by helping to protect native species from invasions and by maintaining favorable soil nutrient and moisture conditions (Gelbard, 2003).

*Prevent and control the spread of invasive species, including pathogens:* Since invasive species may be favored over natives under many climate change scenarios, and cause substantial degradation to grasslands (Stresses and vulnerabilities, pg.33), preventing and controlling their spread is critical for maintaining grassland resilience (Baskin, 1998; Mack et al., 2000; Mooney and Hobbs, 2000).

*Grassland restoration:* Where possible, land managers should conduct grassland restoration, including reintroductions of native species, eradication or control of invasive species, inoculations with soil biota important to native plant vigor, nutrient cycling, and decomposition (e.g., mycorrhizae, biological soil crust organisms), and restoration of native disturbance regimes (Soule and Terbourgh, 1999).

*Maintenance of natural fire regimes:* Fire regimes exert a profound influence on the health and heterogeneity of grassland vegetation (Collins, 1992; Hartnett et al., 1996; D’Antonio, 2000; Ricketts and Dinerstein, 2001). Maintaining or restoring native fire regimes will be an important component of efforts to maintain and restore grassland resilience (Collins, 1992; D’Antonio et al., 2001; Dale et al., 2000).

*Provide buffer zones:* The fixed boundaries of protected areas are not well-suited to a dynamic environment unless individual areas are extremely large (Noss and Cooperrider, 1994; Halpin, 1997; Soule and Terbourgh, 1999). With changing climate, buffer zones might provide suitable conditions for shifting of populations to lands bordering reserves as conditions inside reserves become unsuitable. Another function for buffer zones may be to act as barriers to the spread of new invaders away from roads. For example, establishing strips of dense, ungrazed perennial bunchgrasses, or rocky, infertile substrates may help prevent roadside verges from acting as conduits for the spread of a recently introduced exotic species into the adjacent plant community (Roche et al., 1994; Enloe et al., 2000; Gelbard and Belnap, 2003).

*Identify and protect functional groups and keystone species:* Maintaining the natural diversity of species and functional groups, and dominance (e.g., cover) of native species, is a sound overall strategy for enhancing resilience to climate change (Malcolm and Markham, 1996; Dukes, 2002). Several recent studies have demonstrated increased tolerance to environmental extremes and recovery potential as native species richness or cover increases. For example, Dukes (2002a) found that yellow starthistle *(Centaurea solstitialis)* grown in monoculture responded strongly to $CO_2$ enrichment, increasing aboveground production by 70%, but when grown in competition with common grassland species, showed parallel, but non-significant increases. In some grasslands, native abundance may also increase resistance to invasion, especially at the neighborhood scale (Levine, 2000; Gelbard, 2003). For example, plots dominated by established monocultures of the native perennial grass, *Nassella pulchra,* along with the late season annual forbs, *Hemizonia congesta* and *Lessingia hololeuca* (Dukes 2002b) resisted *Centaurea* invasion. These species, like starthistle, complete their life-cycles late in the growing season and utilize deep soil moisture, suggesting that plant communities are most resistant to invasion where they contain a high abundance of native species with similar life-history characteristics to introduced exotics (Roche et al., 1994; Dukes, 2001, 2002b). It follows that maintaining not only native richness or cover, but also functional group richness, may increase the stability of grassland ecosystems, by increasing the likelihood of protecting native species and life forms with similar life history characteristics to introduced invaders.

*Protect climatic refugia at multiple scales:* It makes sense to identify past climatic refugia wherever possible and focus conservation efforts on these areas so they can again function as refugia during present and future periods of climate change (Noss, 2000).

## Strategies for Protecting and Managing Grasslands Faced with Climate Change

The appropriateness and feasibility of implementing the above adaptations will vary considerably among grassland types, depending on the evolutionary history of their predominant species and the current vulnerabilities of the system. Below, guidelines are provided to help direct decisions concerning how to maximize grassland resilience to climate change.

### LANDSCAPE LEVEL LAND-USE PLANNING

Implementation of many of the proposed adaptations for maintaining and restoring resilience will require conservation-oriented planning that allows examination of local decisions in a regional context (Soule and Terbourgh, 1999; Dale et al., 2000). Optimally, counties, states, conservation organizations, and land trusts should work cooperatively to develop large-scale land use plans that aim to achieve the complementary goals of determining which habitats should receive some form of protection, and which lands are less biologically important and thus suitable for development (Noss and Cooperrider, 1994; Soule and Terbourgh, 1999; Dale et al., 2000).

One objective of landscape planning should be to represent each grassland type, especially its relict communities and sites that contain rare species, in replicated protected areas across environmental gradients, with management appropriate to the native disturbance regime (Current and Future Stress, pg.39). The degree to which this option is feasible will depend on the proportion of habitat that remains intact. Where few if any large patches of native habitat remain, this option will not be feasible. However, where either intact habitats, or degraded, but undeveloped sites suitable for restoration are available, they can be prioritized to receive some form of protection (Noss and Cooperrider, 1994). Additional adaptations that can be considered during the landscape planning process are described below.

### PREVENT AND SLOW THE PROLIFERATION OF INVASIVE SPECIES

When it comes to buffering grasslands against global climate change, a significant challenge will be to protect native communities from the threat of invasive species (Stresses and vulnerabilities, pg.33; Current and Future Stress, pg.39). By virtual consensus, invasion ecologists agree that strategies for achieving this goal should focus on the causes of invasions (such as seed sources and disturbances that increase vulnerability to invasion), not just the invasions themselves (Hobbs and Humphries, 1995; Sheley and Petroff, 1999; Mack et al., 2000). Just as individuals who pay attention to threats posed by an illness after they have become sick are more likely to suffer reduced personal health, resulting in the need for potentially expensive medical treatments, grassland managers who pay attention to threats posed by an invasive species only after their lands have become invaded are more likely to suffer reduced ecosystem health, resulting in the need for expensive control treatments. It is increasingly apparent, moreover, that when it comes to confronting the invasive species problem, an aggressive, prevention-oriented, and adaptive approach is favorable not only ecologically, but also economically (Hobbs and Humphries, 1995; Randall, 1996; Sheley and Petroff, 1999; Mack et al., 2000; Naylor, 2000).

A prevention-oriented approach requires stemming the influx of propagules via the numerous vectors that managers can control, such as vehicles, livestock, outdoor recreationalists, and those related to international trade and horticulture (Mack and Lonsdale, 2001) (it would be virtually impossible to prevent seeds from being introduced via natural vectors such as streams, wind, and native wildlife). This will require persistent monitoring of grasslands adjacent to roads and trails, and in pastures and other hot-spots of seed introduction, as well as rapid eradication of incipient infestations. In addition, it will require coordination with neighboring landowners to prevent adjacent lands from providing seed sources for recolonization.

Preventative management also requires minimizing disturbances that increase grassland vulnerability to invasion, especially those caused by livestock, ORVs, road maintenance operations, and outdoor recreationalists (Sheley and Petroff, 1999). Although the influence of any one of these factors may differ depending on such factors as soil fertility and moisture (Gelbard and Harrison, 2003), and the ecosystem or plant community type (Stohlgren et al., 2001; Harrison et al., 2003) in question, all that are affecting the vulnerability of a site to invasion should be addressed. Examples of possible measures are noted in the paragraphs below.

Attention to detail, as well as political willpower, will make or break invasive species management efforts. For example, both opportunities and restrictions posed by natural climatic variation need to be considered. “Free” years of control provided by climatic extremes such as drought (for some exotic species; e.g., yellow starthistle) and exceptionally wet years (for others; e.g., barb goatgrass; *Aegilops triuncialis)* should be aggressively followed up with at least a second year of eradication treatments, while reseeding of competitive native species may only succeed during exceptionally wet years. The responsiveness of adaptive management, especially the efficiency with which monitoring results are translated into on-the-ground changes, will prove critical to success as managers seek to prepare for the possibility that climate change will accelerate the spread of invasive species.

### PREVENT AND MINIMIZE ROAD IMPACTS RELATING TO INVASIVE SPECIES

Roads are a major key to maintaining grassland resilience to climate change. One of the main reasons for their importance is that climate change is predicted to accelerate the spread of invasive species, and roads provide a major conduit for invasion (Stresses and vulnerabilities, pg.33; Current and Future Stress, pg.39;Strategies for protecting and managing grasslands, pg. 44). Measures that may prove useful for minimizing road impacts include:

Avoiding road construction in roadless habitats and on vulnerable (i.e., more fertile) soil types (Gelbard and Belnap, 2003; Gelbard and Harrison, 2003) to minimize the introductions and spread of invasive species and avoid creating corridors for ORV use and (intentional or accidental) setting of fire;

Carefully timing road maintenance to avoid favoring invasive species and spreading their seeds (Benefield et al., 1999);

Using native species in soil stabilization and revegetation operations to avoid the likelihood of introducing species that could invade neighboring grasslands under changing climatic conditions (Bugg et al., 1997);

Ensuring that roadfill used in road maintenance operations is not contaminated with weed seeds;

Conducting aggressive monitoring of roadside vegetation. This would allow for adaptive management in which roadside maintenance activities can be experimentally manipulated to work toward decreasing both the susceptibility of roadside habitats to invasion and the likelihood that roadside invaders will spread into adjacent natural ecosystems (Gelbard and Belnap, 2003).

## IMPLEMENT SCIENCE-BASED AND ADAPTIVE LIVESTOCK MANAGEMENT STRATEGIES

Since livestock grazing is the predominant use of the world's remaining grasslands and can cause profound ecological impacts (Stresses and vulnerabilities, pg.33; Current and Future Stress, pg.39), this measure will prove critical for maintaining resilience. Too often, grazing practices fail to consider the best available scientific advice concerning how to graze livestock in such a manner as to minimize negative ecological consequences (Archer and Smeins, 1991; Noss and Cooperrider, 1994; Belsky and Gelbard, 2000; Dale et al., 2000; Hobbs, 2001). For example, numerous studies have demonstrated the important role of timing when using grazing as a weed control tool (summarized by Tu et al., 2001), but grazing on commercial ranches is typically continuous (Wagner, 1989), with livestock rarely if ever removed or rotated during times known to favor invasive species. In many cases, this is likely due to a lack of flexibility on commercial ranches (Tu et al., 2001), but in others it may simply be due to lack of awareness of timing effects. Appropriate grazing strategies will differ by ecosystem, and local environmental conditions (Harrison et al., 2003), but may include:

Limit grazing to habitats where native species and soil biota are adapted to it (Baker, 1978; Mack, 1989), and to degraded habitats where invasions are likely to worsen following livestock removal (e.g., Brenton and Klinger, 1994). Nurturing the recovery of soils and native vegetation following livestock removal requires a long-term view, especially in more arid systems (e.g., Brejda, 1997; Anderson and Inouye, 2001; Valone et al., 2002). Native recolonization may require not only a native seed source, but also climatic conditions that occur only once every decade or longer. Recovery of many native species may also be more pronounced on sites characterized by favorable moisture conditions (Billings, 1990; Belsky and Gelbard, 2000). For example, after 58 years of protection from grazing in the western United States, native plant density and cover increased on northern exposures, although not on southern and western exposures (Monsen, 1994). The same holds true for declines in exotic species following livestock removal, as demonstrated in British Columbia, where cheatgrass began to decline only after 30 years of exclusion (McLean and Tisdale, 1972).

Design management on a site-specific basis depending on soil and moisture conditions, the predominant native species, life forms, and exotics that pose a threat (Noss and Cooperrider, 1994; Randall, 1996; Holecheck et al., 1998). Altering the timing, intensity, and duration of grazing as well as the type of grazing animal may all help to minimize negative impacts to native species and soils (Archer and Smeins, 1991; Holecheck et al., 1998; DiTomaso, 2000; Belnap and Lange, 2001; Masters and Sheley, 2001);

Conduct intensive monitoring as part of adaptive management to minimize excessive disturbances to vegetation and soils (Noss and Cooperrider, 1994).

By preventing and minimizing selective grazing of palatable native species, limiting the extent of trampling disturbances that reduce soil water capacity and injure native plants, maintaining nutrient cycles and biological soil crusts, minimizing the spread of invasive species, and maintaining native disturbances regimes, the above livestock management measures will help to protect and enhance grassland resilience, including to climate change.

#### GRASSLAND RESTORATION

The vast area of grassland habitats that are currently degraded undoubtedly makes the task of restoration appear daunting. In grasslands where exotic annuals have overrun large expanses of habitat, such as those in Australia (Hobbs, 2001), Chile (Arroyo et al., 2000), California (Heady, 1995), and the Intermountain West, USA (Mack, 1989), a long-term, multi-pronged strategy involving restoration of the native disturbance regime (including letting natural fires burn, conducting controlled burns, and, where necessary, removing livestock), re-introductions of native species and soil biota, and eradication or control of invasive species will likely be needed (Soule and Terbourgh, 1999; U.S. Bureau of Land Management [BLM], 1999; Belnap and Lange, 2001).

Of course, the appropriate tools may or may not be available, depending on the location of a site (Soule and Terbourgh, 1999). For example, controlled burning is not feasible and may be illegal in more developed or air pollution-sensitive areas. It may also require some type of incentive if it is to be conducted on many private lands, where ranchers lose that forage for a season. In addition, since natural fires sometimes hinder restoration and recovery (D'Antonio, 2000; Harrison et al., 2003), some degree of fire suppression may still be required (Soule and Terbourgh, 1999). In grasslands that remain relatively intact, such as those of the Great Plains, USA (Ricketts and Dinerstein, 2001), management improvements combined with native reseeding and weed control are more likely, in the short-term, to restore grassland components important to resilience. Since the science of grassland restoration remains in its early stages (Young, 1999), an adaptive approach will almost certainly be needed to restore and maintain the composition and structure of grasslands faced with climate change.

### Recommendations for Action and Policy

Policy and management actions required to implement the above strategies include measures that can be implemented at international, federal, state, county, community, and individual levels. At the international level, for example, considerable changes to trade policies will be needed to help stem the introductions and spread of invasive species, and such policies will need to be vigorously defended in both biological and economic terms in World Trade Organization dispute panels (McNeely, 2000; Van Driesche and Van Driesche, 2001). At national, state, and local levels, appropriate measures will often differ between public and private lands, and perhaps among cultures (Dale et al., 2000).

Private landowners will need financial impetus and know-how to implement the suggested adaptations. It will be important for governmental agencies and non-governmental organizations (NGOs) to use incentives to convey a sense that changing management will provide an opportunity to improve economic well-being and quality-of-life. Conversely, incentives that accelerate habitat loss by encouraging suburbanization, such as tax deductions for home mortgage interest payments, and duties that discourage conservation, such as expensive estate taxes that landowners can sometimes only pay by subdividing grasslands, should be replaced with incentives for conservation (Myers and Kent, 1998; Dale et al., 2000). The same holds true for subsidies for agriculture, water use, and roadbuilding throughout the world, without which many grassland habitats could not affordably be converted to or maintained as agriculture, overgrazed, or roaded (Myers and Kent, 1998).

It will also be important to educate the public about the availability of incentive programs. Both NGOs and governmental agencies will prove key as grassland owners seek assurances that taking steps to increase resilience will not threaten their livelihoods. Financial and quality-of-life concerns must be addressed by providing both direct (e.g., conservation easements, conservation rewards, safe harbor agreements, habitat conservation plans, grants, cost-share programs) and indirect (e.g., education, technical support) benefits to make grassland conservation and restoration economically and socially desirable, and thus more politically feasible (McNeely, 2000; Dasgupta et al., 2000; Dale et al., 2000; Naylor, 2000).

On public lands, implementing the recommended strategies for maintaining resilience will require changes—some major and some minor—to existing land use policies and management plans (Dale et al., 2000). For example, subsidies, without which livestock grazing on marginal habitats would not be economically feasible for many ranchers in the western United States, should be eliminated to allow market forces to influence the decision of whether grazing can continue (Myers and Kent, 1998). Similarly, cuts to government spending on the maintenance of existing, but non-essential roads could provide an incentive to close seldom-used roads that may still be acting as corridors for the spread of invasive species. In addition, an incentive to change road maintenance schedules to avoid exacerbating invasions could be created by making eligibility for international or federal transportation grants contingent on implementing the proposed adaptations. This could help, for example, to stem the problem of roadside mowing to prevent fire often resulting in the dominance of roadside grasslands by noxious weeds (Benefield et al., 1999).

Implementing the proposed adaptations will undoubtedly pose considerable challenges. The most effective options for maximizing resilience may not always appear socioeconomically feasible, may not be legal, and may meet with considerable political resistance (Lee, 1993; Walker and Steffen, 1997; Soule and Terbourgh, 1999). Take for example the issue of restoring native fire regimes. From a scientific standpoint, a mixed strategy in which managers let natural fires burn and conduct controlled burns in systems where frequent fire is important for maintaining native vegetation, but suppress fire in grasslands where it is naturally infrequent (e.g., Sagebrush/bunchgrass steppe; West, 1983), might be appropriate. In the short-term, however, translating this scientific information into appropriate fire policy and management decisions is sure to prove contentious. While economic benefits of such an approach (e.g., reduced cover of invasive species, increased forage quality) could increase public support for this type of fire policy in the long-term, such adaptations are unlikely to succeed without broad public support from the beginning (Soule and Terbourgh, 1999). Thus, in addition to devising management strategies to maintain and restore resilience, ecologists and land managers will need to work together with economists, sociologists, communication specialists, policymakers, and the public to devise economic and public relations strategies aimed at gaining the support of skeptical policymakers and landowners (Lee, 1993; McNeely, 2000; Robertson and Hull, 2001; Dale et al., 2000).

Communication and education strategies may include illustrations of how delaying management improvements might prove more costly than taking immediate action (e.g., Walker and Steffen, 1997; Naylor, 2000; Ayres, 2001). Management guidance and education materials can be made available via direct mailings, over the internet via public outreach, at local farmers' markets and community centers, and at meetings of involved stakeholder organizations such as commerce, farming, ranching, and outdoor recreation associations.

Funding for devising and implementing adaptations, typically a critical factor limiting the effectiveness of such functions as adaptive management, may come from international organizations such as the United Nations (e.g., UNEP), International Union for the Conservation of Nature, the World Commission on Protected Areas, and the Global Environment Facility. National organizations such as the United States Invasive Species Council, state-level agencies such as agriculture and transportation departments, and private foundations may also provide financial support. Technical expertise for implementing adaptations could be provided by groups such as NGOs, and university experts and graduate students.

### Examples of Existing Adaptations

Changes in grassland management that promote resilience are already being implemented on both public and private lands. In the southwestern United States, the Malpais Borderlands Group—a coalition of ranchers, state and federal agencies, The Nature Conservancy, and private foundations—have banded together to devise a grass-banking approach to conservation and restoration. Ranchers whose lands have suffered sufficient declines in productivity to limit their ability to graze livestock are now threatened with the prospect of subdividing their lands to provide needed income. However, by joining the group, they can gain access to a grass bank on which to graze livestock—the 110,000 hectare Gray Ranch—and receive restoration and recovery treatments such as native reseeding and rest from grazing, as well as technical assistance and monitoring from grassland management experts, in exchange for taking steps such as (1) donating a conservation easement on their land to the group, which conserves grassland habitat by maintaining their ranch as open space, while providing economic benefits such as reduced estate taxes; and (2) allowing natural fires to burn, which helps beat back invasive woody plants and stimulates the recovery of native grasses and wildflowers (Page, 1997). Of course, risks such as degradation of the grassbank, itself, will need to be avoided, and this approach to grassland conservation and restoration remains an experiment in progress. However, the Malpais Group has clearly devised an innovative approach for landscape-scale conservation of privately owned grasslands, one that can certainly be modified to serve as the basis for other large-scale private lands conservation efforts.

An emerging approach with intriguing prospects for improving the health of publicly-owned grasslands is voluntary retirement of public lands grazing permits in the western United States (Salvo and Kerr, 2001). To encourage livestock removal from public lands where soils and native species are vulnerable to or have been degraded by livestock impacts, NGOs are seeking to facilitate the purchase of grazing permits for above-market value. This program would provide an opportunity for private land owners to cash in on the value of their public lands grazing permits, without the loss of their public grazing leases increasing pressure on them to subdivide and develop their privately-owned parcels. Removing livestock from these public lands, in turn, would reduce the considerable deficits that the federal government incurs through its public lands grazing program (Myers and Kent, 1998), including by (1) maintaining livestock infrastructure on marginal lands, (2) repairing livestock-caused degradation, and (3) controlling predators. It would increase resilience to climate change by allowing for restoration of native disturbance regimes, plant communities, and soils on grasslands where livestock are an exotic ecological force.

Finally, the practice of grassland restoration is accelerating (Harnett et al., 1996; DiTomaso et al., 1999, 2001; US BLM, 1999). Due to the increasing realization that establishment of native species will require restoration of native disturbance regimes, land managers are conducting controlled burns and reintroducing native herbivores (Menke, 1992; Harnett et al., 1996; DiTomaso et al., 1999). Although many of these practices require continued research, preliminary results are encouraging (e.g., D'Antonio et al., 2001). For example, three years of controlled burns almost entirely eliminated the cover and seed production of yellow starthistle and increased native bunchgrass cover by more than five-fold (DiTomaso et al., 1999). In a tallgrass prairie, bison grazing and prescribed fire resulted in significant increases to plant species diversity and spatial heterogeneity (Hartnett et al., 1996).

By recognizing that land management should differ among grasslands depending on their natural disturbance regime, environmental conditions, and conservation status, by reigning in destructive land use practices, and, where possible, by restoring habitats, including through the use of incentive-based conservation strategies, scientists, land managers, policymakers, and the public can work together to maintain and restore the resilience of grassland ecosystems to climate change. Of course, this chapter has provided only a general overview of potential adaptations, and the ability of the proposed strategies to confer resilience is not limitless in relation to climate change. For example, while these measures are most likely to be effective, in the short-term, in less degraded grasslands, they may take decades to restore resilience in thoroughly degraded grasslands. Even then, if governments and corporations continue to resist the need for decisive measures to address the ultimate causes of climate change, such as the growing human population's greenhouse gas emissions and conversion of natural habitats to human uses (Schlesinger, 1997), there may be little that land managers can do to prevent continued degradation, fragmentation, and loss of grasslands. At a time when humanity has reached a crossroads, in one direction faced with a growing extinction crisis that is certainly affecting grasslands (Sala et al., 2000), while in the other faced with the possibility that environmental solutions abound with opportunities to improve economy and quality-of-life (Myers, 1996; Daily et al., 1997; Myers and Kent, 1998; Dasgupta et al., 2000), we owe it to ourselves and to future generations to protect and maintain the world's grasslands from the potential consequences of global climate change.

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WWF Climate Change Program
Director
Jennifer Morgan
c/o WWF Germany
Große Präsidentenstraße 10
10178 Berlin
Germany

Tel: +49 30 308 742 20
Fax: +49 30 308 742 50
Website: www.panda.org/climate

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