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Nature's Services: Societal Dependence on Natural Ecosystems
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Chapter 13

ECOSYSTEM SERVICES IN GRASSLANDS

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The grassland biome covers an enormous fraction of the surface of the earth. Grasslands are the potential natural vegetation of approximately 25 percent of the land surface of the earth, or 35×10^6 Km^2 (Shantz 1954, Graetz 1994) . These are systems mostly limited by water, which are dominated by grasses and have a variable woody component. Humans utilize these areas as grazing lands or transform them into croplands depending mostly on water availability and the amount of subsidies received by agriculture in each individual country. Most of the mesic grasslands have been converted into agricultural land, whereas a large fraction of the arid and semi-arid grasslands remain as such. Subsidies to agriculture make transformation of grasslands into croplands economically feasible in regions that otherwise would remain as native grasslands, such as the western portion of the North American Great Plains (Hannah et al. 1995).

Grasslands produce an array of goods and services for humankind, but only a few of them have market value. Meat, milk, wool, and leather are the most important products currently produced in grasslands that have a market value. Simultaneously, grassland ecosystems confer to humans many other vital and often unrecognized services such as maintenance of the composition of the atmosphere, maintenance of the genetic library, amelioration of weather, and conservation of soils. The fact that humans take for granted the provision of these grassland services is not an indication of their value. In many cases, the value of services provided by grasslands in terms of production inputs and sustenance of plant and animal life (see chapter 3 by

Goulder and Kennedy in this book) may be larger than the sum of the products with current market value.

this chapter we will focus on those services that currently have no market price and for which society has difficulty in assessing value. We will discuss the role of natural grasslands in maintaining the composition of the atmosphere and the genetic library, as well as ameliorating the weather and conserving the soil. Our approach will be to compare natural grasslands under moderate grazing with alternative land uses, which include drastic changes such as transformation into croplands and more subtle changes that grasslands undergo when grazed with different intensities. We will evaluate the ecological effect and the economic value of these changes in land-use practices.

Maintenance of the Composition of the Atmosphere

Grasslands sequester in the soil large quantities of carbon (C) as soil organic matter, which are rapidly transferred into the atmosphere when plowed and converted into agricultural land. In comparison with other ecosystems such as forests, grasslands store most of their C belowground (Burke et al. 1989, Moraes et al. 1995). Carbon stocks in grasslands are largely determined by abiotic factors; they increased with precipitation mainly as a result of increased primary production (input) and decrease with increasing temperature as a result of increased decomposition (output) (Burke et al. 1989).

Tillage associated with the transformation of grasslands into croplands increases soil organic matter decomposition and decreases carbon stocks mainly as a result ofbreaking soil aggregates and exposing residues to decomposers (Elliot 1986). Carbon losses as a result of cultivation are very large. Results of a study comparing native and cultivated soils in the Great Plains of the United States indicated that cultivation resulted in C losses ranging between 0.8 and 2 kg m^{-2} when the average C content of soils for the region ranges between 2 and 5 kg m^{-2} (Burke et al. 1989) (figure 13.1).

Carbon losses as a result of cultivation vary according to climate and site characteristics, increasing with precipitation and silt content and decreasing with temperature (Burke et al. 1989). In general, C losses as a result of cultivation track C stocks, with larger losses occurring in soils with larger C stocks (figure 13.1). The loss of carbon as a result of cultivation of grasslands occurs very rapidly, but recovery after abandonment occurs at a slower rate. For example, in the Great Plains of North America C stocks after plowing decreased significantly and very rapidly.(Cole et al. 1989), but after fifty years of abandonment stocks had not yet reached the levels of native soils (Burke et al. 1995, Ihori et al. 1995).

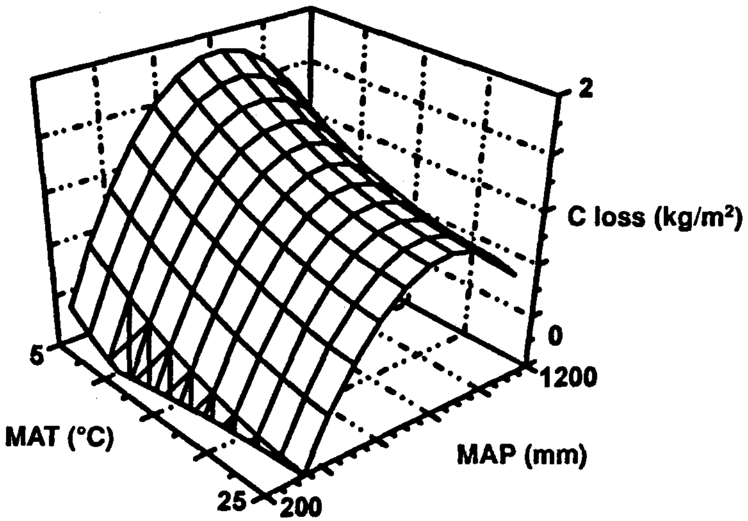

Figure 13.1. Abiotic controls on the amount of carbon lost as a result of cultivation in the Great Plains of North America. MAT is mean annual temperature and MAP is mean annual precipitation. Carbon loss is the difference in C stocks between cultivated and native soils for different locations in the Great Plains of North America.
Source: Redrawn from Burke et al. 1989.

At a global scale, agriculture has made a significant contribution to the observed increase in atmospheric CO_2. Analysis of tree rings, which are indicative of the CO_2 concentration of the atmosphere in the past, showed that the rapid transformation of native ecosystems into croplands that occurred between 1860 and 1890 contributed one and a half times the amount of CO_2 produced by all the fossil fuel emissions through 1950 (Wilson 1978).

The transformation of grasslands into croplands significantly contributes to the global increase of the atmospheric concentration of CO_2. Changes in the concentration of CO_2 have multiple direct effects on the functioning of plants and animals (for a review see Bazzaz 1990). Here we will focus on the very important indirect effect of increasing CO_2 on climate. There is general agreement that increases in the atmospheric concentration of trace gases such as CO_2, methane, nitrous oxide, and CFC's will result in disruptions of global climate systems (Mitchell et al. 1990).

Carbon loss from grasslands contributes to the global CO_2 increase and to climate change. The effects of increasing CO_2 on climate are expected to be major. For example, doubling of the concentration of CO_2 in the atmosphere will result in an increase of the temperature of the earth ranging between 1.5 and 4.5 °C and in an increase of global precipitation parallel with an increase in evaporation ranging between 3 and 15 percent (Mitchell et al. 1990). Most of the uncertainties are now reduced to the timing and the geographical distribution of those changes. Climate change results from several factors changing simultaneously. Most recent projections suggest an increase between 2.0 and 2.4 ^{O}C by the year 2100 (Kattenberg et al. 1995).

These disruptions of the climate system will have a negative impact on a majority of countries, mostly through impacts on agricultural production (Paruelo and Sala 1993, Rosenzweig and Parry 1994). The size of the impact varies according to the climate scenario chosen and the geographical location of the country (Kane et al. 1992). Based upon ecological and economic information briefly described above, scientists have been able to develop models that estimate the costs of adding carbon to the atmosphere (Nordhaus 1991, Fankhauser and Pearce 1994).

The costs of CO_2 emissions have been estimated based on the negative effects that increasing CO_2 has on climate: $20.4 per tonne of C for the period 1991-2000, $22.9 for 2001-2010, $25.4 for 2011-2020, and $27.8 for 2021-2030 (Fankhauser and Pearce 1994). The costs of CO_2 emissions increase through time because an extra tonne of CO_2 added to an already large stock of atmospheric CO_2 will result in more damage than a tonne emitted when CO, was low. Based on the estimates of the effects of cultivation on C stocks and the estimated costs of CO, emissions described above, we calculated the value of carbon sequestration in grasslands to be $200 per ha with a range between $160 and $400/ha (table 13.1).

The value of carbon sequestration by grasslands is large compared to the value of land and the annual production of goods with market value such as meat, wool, and milk. The market value of land for counties in eastern Colorado (U.S.) ranges between $311 and $1,633/ha with a direct average of $798/ha (U.S. Department of Commerce 1995). The net cash return for farms in the same region ranges between $5 and $144/ha/yr with an average of $47/ha/yr. This comparison of the services with nonmarket value, such as carbon sequestration, against the market value of goods and services is valid since both are based on data from the same region. Our estimates of the impact of cultivation on CO_2 emissions, the value of carbon sequestration, as

Table 13.1. The value of maintaining native grasslands: Carbon sequestration

Carbon loss	10×10^3 kg/ha[a]
Cost	$0.02 per kg of C
TOTAL	$200/ha

[a] Values observed ranged between 8×10^3 kg/ha and 20×10^3 kg/ha.

well as the value of land and production were based on data from eastern Colorado.

We want to stress the hysteresis of this process; while transformation of grasslands into croplands yields large amounts of C to the atmosphere in a relatively short period of time, the reverse process of abandonment of crop lands and their slow transformation into native grasslands sequesters only modest amounts of carbon over relatively long periods of time (Ihori et al. 1995). A study of C accumulation showed that after fifty years of abandonment, C stocks increased 3,000 kg/ha, which results in a value of $60/ha or $1.20 $ha^{-1}yr^{-1}$ (Burke et al. 1995, Ihori et al. 1995).

Agriculture and the transformation of grasslands also affect the dynamics of other trace gases such as methane and nitrous oxide. Both are active greenhouse gases in that they are transparent to the radiation of the sun but absorb radiation emitted by the earth. Therefore, increases in the atmospheric concentration of trace gases lead to increases in the temperature of the earth and severe disruptions of the climate system.

Field experiments comparing native grasslands and adjacent cultivated plots have shown that cultivation decreases the uptake of methane and increases the emissions of nitrous oxide, contributing to the increasing concentrations of these gases in the atmosphere (Mosier et al. 1991). The absolute quantities of carbon that are emitted as methane and its concentration in the atmosphere are quite small compared to CO_2. However, methane has a greenhouse effect that is twenty to fifty times larger than CO_2 (Shine et al. 1990). The energy emitted by the earth comprises a range of wavelengths, and different greenhouse gases absorb in different wavelengths. Methane absorbs in a range of wavelengths, where current absorption is quite low, and therefore small additions of this gas into the atmosphere will result in large changes in the greenhouse effect and the temperature of the earth.

Field experiments showed that native grasslands take up 2.6 g C ha^{-1} d^{-1} as methane, while adjacent wheat fields uptake only half of this magnitude (Mosier et al. 1991). The cost of methane emissions has been calculated in a similar manner as that described for the cost of CO_2 emissions (Fankhauser and Pearce 1994). Combining information about the effect of cultivation and the cost of methane emissions, we calculated the current annual costs of cultivation associated with methane emissions (table 13.2). As in the case of CO_2, the cost of methane emissions increases with time. Therefore, the cost for the forty-year period 1991–2030 is forty times larger than the cost of emissions in 1991.

Nitrous oxide is also a trace gas with greenhouse effect; its greenhouse effect is two orders of magnitude larger than CO_2. Nitrous oxide is emitted by grasslands and croplands, but croplands emit at a higher rate than native grasslands, and this rate is even larger in fertilized than in unfertilized crops

Table 13.2. The value of maintaining native grasslands: Methane uptake

Methane uptake	**0.474 kg C ha^{-1} yr^{-1}**
Methane cost	**\$0.11/kg CH_4**
Current annual cost	**\$0.05/ha**
Projected cost for 1991 to 2030	**\$2.70/ha**

Table 13.3. The value of maintaining native grasslands: Nitrous oxide emissions

Nitrous oxide emissions	**0.191 kg N ha^{-1} yr^{-1}**
Nitrous oxide cost	**\$2.94/kg of N**
Current annual cost	**\$0.60/ha**
Projected cost for 1991 to 2030	**\$28.50/ha**

(Mosier et al. 199 1). The damage caused by nitrous oxide emissions is even greater than the cost of methane and CO_2 emissions because of its larger greenhouse effect (Fankhauser and Pearce 1994). We estimated the annual and the accumulated nitrous oxide emission costs for the period 1991-2030 based upon the difference in emissions between grasslands and adjacent wheat fields and the cost per unit of nitrogen emitted as nitrous oxide (table 13.3).

The costs of emissions of methane and nitrous oxide associated with cultivation are small when compared with the costs of CO_2 associated with transforming grasslands into croplands. We need to take into account that cultivation releases huge amounts of carbon as CO_2 after cultivation only once (during a relatively short period of time). The annual benefits of capturing CO_2 after returning croplands into grasslands are much smaller, and they are comparable to the annual benefits associated with reductions in methane and nitrous oxide emissions from maintaining grasslands as such.

Genetic Library

Grasslands provide an important service to humans by maintaining a large storehouse of genetic material referred as the genetic library. Norman Myers thoroughly describes the ecosystem services associated with the maintenance of the genetic library (see chapter 14 of this book). In this section we instead recognize the uniqueness of grasslands for their contribution to maintaining a global genetic library. Semi-arid systems are particularly important in terms of their biological diversity. For example, drylands in South America are richer in number of mammal species, and have more endemic taxa, than lowland Amazonian rainforest (Mares 1992). This is partially the result of the huge area covered by arid and semi-arid ecosystems.

Another important aspect of grasslands is that the majority of the centers of origin of domesticated plants and animals are located within water-limited systems, primarily composed of grasslands (Vavilov 1951, McNeely et al. 1995). These are the ecosystems where annual grasses and legumes are most abundant. Wheat, barley, onions, and peas all share the same center of origin in the grasslands of the Mediterranean region, in an area known as the Fertile Crescent, which extends from Greece eastward. This area also is the center of origin of many domesticated animals such as goats, sheep, and cattle.

Therefore, the genetic resources of grasslands have a disproportionately large conservation value for humans, who depend on a limited number of grassland species for nutrition, medicine, fiber, and shelter. Grasslands represent the natural ecosystem from where a large fraction of domesticated species originated, and where wild populations related to the domesticated species and their associated pests and pathogens still thrive. These areas are most likely to provide new strains that are resistant to diseases or contain new features important for humankind.

Amelioration of Weather

Changes in the utilization of grasslands, such as those resulting from differential grazing intensity and ultimately overgrazing, as well as the more drastic transformation of grasslands into croplands, have important effects on climate at different scales. We will attempt to demonstrate here that moderately grazed natural grasslands provide a valuable service to humans by ameliorating climate.

Grazing results in changes in the structure of the community and in the composition of plant species in the Patagonian steppe (León and Aguiar 1985). Cover of the grasses preferred by sheep decreases and bare soil groundcover increases along a gradient of increasing grazing intensity. After a threshold in grass cover is crossed, a largely unpalatable shrub *(Mulinum spinosum)* invades, and its dominance continues to increase. These changes in community structure and composition result in changes in albedo, which is the amount of energy reflected by the land surface (Aguiar et al. 1996) (figure 13.2). From light to moderate grazing intensity, there is an increase in the amount of energy reflected, which is related to a decrease in plant cover and an increase in bare soil. Further increases in grazing intensity result in the invasion of the shrub *Mulinum spinosum,* with the resulting increase in cover and decrease in albedo. Besides changes in albedo, grazing also modifies vegetation roughness length, another parameter affecting climate, which varies from 0.02 m in the grassdominated portion of the gradient to 0.09 m in the shrub-dominated portion of the gradient. These changes in roughness length have the potential to alter local circulation patterns and regional climate.

Similar changes in community structure and climate have been observed along the U.S.-Mexico border (Balling 1988, Bryant et al. 1990). As a result of differences in land use between the two countries, there is a sharp difference in community structure along the border in what was once the same community with the same climate. The Mexican side has lower grass cover and correspondingly more bare ground. The lower plant cover results in higher albedo, as in the Patagonian case. The increase in reflectance has been suggested to decrease temperature and convective precipitation, leading to a positive feedback toward desertification, where overgrazing leads to lower precipitation, lower primary production, and (if stocking rate remains constant) further overgrazing (Charney 1975). Comparison of long-term climate data sets of the Sonoran Desert on both sides of the US.-Mexico border showed that the Mexican side was 2.3°C warmer than the U.S. side.

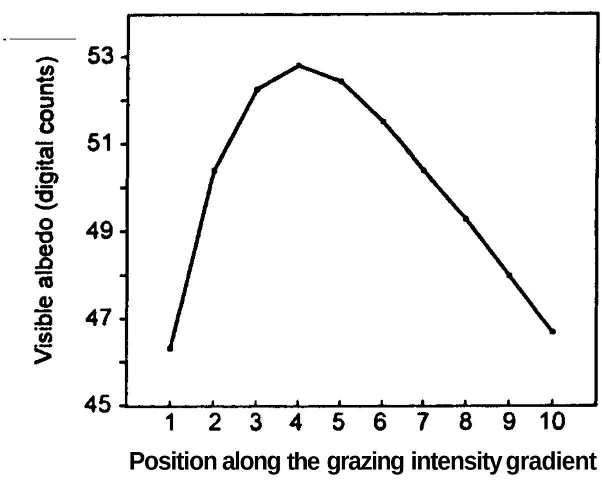

Figure 13.2. Changes in albedo, which is the fraction of incoming solar radiation reflected back into the atmosphere, along a gradient of grazing intensity from light to heavy grazing.
Source: Redrawn from (Aguiar et al. 1996).

These data do not support the Charney (1975) hypothesis, suggesting that the decrease in plant cover reduces transpiration and the energy loss by means of latent heat. Reduced transpiration seems to be more important in altering climate than does the decrease in energy absorbed as a result of increased reflectance.

The drastic transformation of grasslands into agricultural land modifies the energy balance of a region (figure 13.3). The effect of a shift from a grassland into a wheat field or into wheat-soybean relay double cropping system on the energy balance is documented by the changes in the Normalized Vegetation Difference Index (NDVI). The NDVI is an index derived from the reflectance in the red and infrared bands measured by satellites, which shows strong correlation with vegetation attributes such as biomass and production (Running 1990). The three land cover types differ in the seasonal dynamics of the NDVI, reflecting seasonal change in leaf area, albedo, and evapotranspiration. Pielke et al. (in press) showed that these types of changes in land use may affect significantly the mesoscale climate.

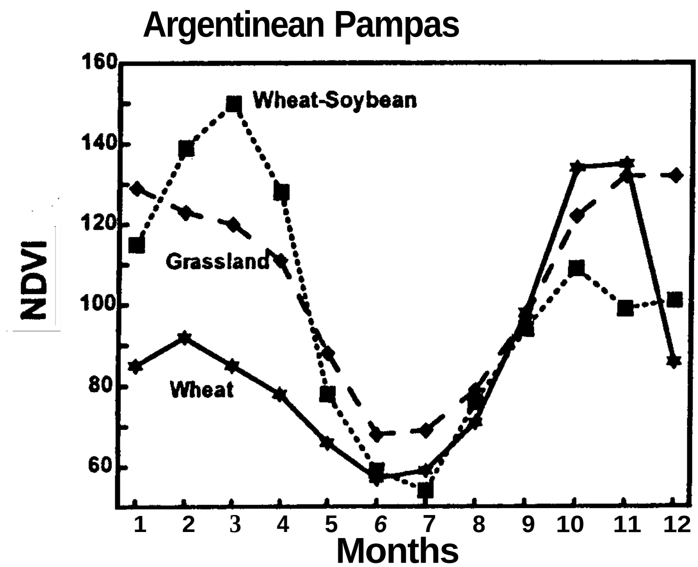

Figure 13.3. Changes in the quality and the amount of energy reflected as a result of transforming native grassland into different kinds of agricultural land. Annual pattern of the Normalized Vegetation Difference Index (NDVI) for a native grassland, a wheat field, and double cropping wheat-soybean in the Argentinean Pampas. The NDVI is an index derived from the reflectance in the red and infrared bands measured by satellites, which is strongly correlated with leaf area, biomass, and primary production.

Table 13.4. Regional climate modeling exercise for North America: The Central Plains case

	Current	Natural	Difference
Temperature (K)	296.15	295.99	0.16
Precipitation (mm d-I)	3.83	3.65	0.18

Source: Copeland et al., *Journal of Geophysical Research* (in press).

We have described examples in which variations in grazing intensity or agricultural use have resulted in changes to the local climate by means of changes in albedo, roughness length, and evaporation. Do these effects scale up, and can they be seen at the regional level? This question cannot be answered experimentally because there are very few regions identical with respect to climate but with different land-use patterns. This large-scale question needs to be answered using simulation models.

An exercise that used a climate model that operates at regional scales (Pielke et al. 1992, Pielke et al. 1996) allowed a detailed comparison of climate under potential natural vegetation and under current land-use conditions (Copeland et al. in press). The exercise was limited to the continental United States, where 60 percent of the area has been modified from the original potential natural vegetation. For the purpose of this chapter, we focused exclusively on the Central Plains region of the United States. This area was originally entirely covered by grasslands and currently contains a combination of croplands and native grasslands. This region still maintains a relatively large area as native grasslands because of water limitation on agricultural production. Current changes in land use in the North American Great Plains are estimated to have already caused warmer conditions, mainly as a result of the reduction of green cover and transpiration during part of the year (table 13.4). Precipitation has increased slightly, which still is of great importance for a region where the average precipitation is low and ranges between 300 and 1,000 mm yr^{-1}.

Conservation of Soil

Increases in grazing intensity result in profound changes in the functioning of ecosystems. We have already discussed esamples indicating how grazing modifies plant and bare soil cover. More subtle changes occur as a result of grazing before changes in cover, which include changes in plant species composition and soil conditions, are evident (Sala et al. 1986, Chaneton and Lavado 1996). The range science literature has abundant examples demonstrating that heavy grazing and overgrazin have negative impacts on soil erosion (Branson et al. 1981). Most of the effects of grazing on soil erosion are related to the reduction in plant biomass and cover, as well as to the increase in bare ground. Animals have also a direct effect on grasslands by trampling and compacting the soil surface, which in some cases decreases water infiltration and consequently increases runoff and soil erosion. Heavily grazed plots, in Colorado in the United States, showed double the erosion rate of moderately grazed or ungrazed plots (Dunford 1949). Similarly, in grasslands of western Texas it has been shown that a clear relationship exists between plant biomass (which is controlled by grazing) and sediment yield (Bedunah and Sosebee 1986).

Humans have a more drastic impact on erosion when they plow grasslands and transform them into croplands. A comparison of two crops, wheat and sorghum, versus a native grassland in Texas, shows almost negligible soil losses in the native grassland and huge losses (on the order of tons per ha) in any of the crop systems (figure 13.4) (Jones et al. 1985). It is clear that grasslands provide an important service by controlling soil erosion.

Erosion results in multiple on-site and off-site costs. On-site costs are those occurring within the piece of land under consideration and are those that ranchers and farmers are usually most concerned about. This kind of cost accounts for losses in production potential, infiltration, water availability, and nutrient availability. Off-site erosion costs include expenditures such

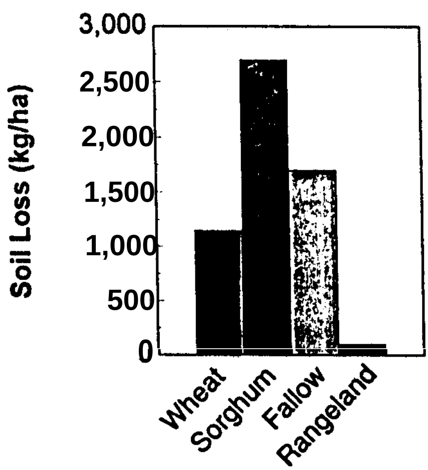

Figure 13.4. Soil loss as a function of land use, wheat, sorghum, fallow, and rangeland. Results are six-year averages.
Source: Redrawn from Jones et al. 1985.

as the increased costs of obtaining a suitable water supply, maintaining navigable channels and harbors, increased drainage problems, increases in flood damage, increased costs of maintaining roads, and a decreased potential for water power. In economic terminology, off-site erosion costs are "externalities" to the production process.

The off-site costs of erosion to society are huge. In the United States, the off-site erosion costs are 817 billion per year (using 1992 dollars) (Pimentel et al. 1995). This enormous cost occurs in a country that has a moderate erosion rate of seventeen tons ha^{-1} yr^{-1} as a result of investment in technology and erosion control mechanisms. Poorer countries in Asia, Africa, and South America average much larger erosion rates of forty tons ha^{-1} yr^{-1}. The on-site costs for the United States are also quite high, $27 billion per year. The magnitude of the erosion problem can be appreciated when costs are scaled up to national or global levels. In the United States the total cost of soil erosion is $44 billion per year, or $ 100 per hectare of cropland or pasture. At the global level, soil erosion is enormous (75×10^9 tons of soil), which results in costs of $400 billion per year or $70 per person per year (Pimentel et al. 1995).

Conclusions

Grasslands provide humans with many services, most of which currently have no market value. Native grasslands contribute to maintaining the composition of the atmosphere by sequestering carbon, absorbing methane, and reducing emissions of nitrous oxide. Grasslands maintain a large genetic library, ameliorate regional climate, and preserve the soil from devastating erosion. Our estimates suggest that, in many cases, the value of these services are comparable to the value of the services that have a market value, such as production of meat, wool, and milk.

Hysteresis in the ability of grasslands to provide services is a pervasive phenomenon. Grasslands contain large quantities of carbon in their soils that are rapidly released into the atmosphere when plowed. However, the reverse process of accruing carbon is very slow. Similarly, native grasslands represent a reservoir of biological diversity, which is rapidly depleted after cultivation or overgrazing. Recovery of diversity is very slow, or may never occur, depending on the size of the disturbed area.

The underestimated value of grasslands has consequences for decision makers, researchers, and society as a whole. Errors in valuation may lead to inappropriate decisions on the fate and best use of natural resources for society. The ability to provide goods and services with market value is not necessarily related to the ability to provide other services that currently may not have a market value. Ignoring the value of services with no market value may be seriously misleading.

Research efforts are guided either by scientific curiosity or by problem-solving needs. Scientific curiosity is the most important driving force accounting for the major accomplishments of humankind in understanding the functioning of nature. However, in many instances, scientific curiosity also has led to major applications. The search for solving problems is the most important motivation for applied research, but in many instances, it has also illuminated basic issues. Not recognizing all the services provided by grasslands misled scientists since all of the applied management questions are aimed at maximizing the production of goods and services with market value. Large numbers of studies of grazing systems trying to maximize meat production contrast with scarce or nonexistent studies of management techniques aiming at maximizing biological diversity, carbon sequestration, or soil preservation.

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References

Aguiar, M. R., J. M. Paruelo, O. E. Sala, and W. K. Lauenroth. 1996. "Ecosystem responses to changes in Plant Functional Type composition: An example from the Patagonian steppe." *Journal of Vegetation Science 7:* (in press).

Balling, R. C. 1988. "The climatic impact of a Sonoran vegetation discontinuity." *Climatic Change* 13:99-109.

Bazzaz, F. A. 1990. "The response of natural ecosystems to rising global CO_2 levels." *Annual Review of Ecologv and Systematics* 21:408-414.

Bedunah, D. J., and R. E. Sosebee. 1986. "Influence of mesquite control on soil erosion on a depleted range site." *Joural of Soil and Water Conservation* 41:131-135.

Branson, E, G. Gifford, K. Renard, and R. Hadley. 1981. "Runoff and water harvesting." In: *Rangeland Hydrology,* E. H. Reid, ed., pp. 73-110. Dubuque, Iowa: Kendall/Hunt Publishing Company.

Bryant, N. A., L. E Johnson, A. J. Brazel, R. C. Balling, C. F. Hutchinson, and L. R.

Beck. 1990. "Measuring the effect of overgrazing in the Sonoran Desert." *Climatic Change* 17: 243-264.

Burke, I. C., W. K. Lauenroth, and D. P Coffin. 1995. "Soil organic matter recovery in semiarid grasslands: Implications for the conservation reserve program." *Ecological Applications* 5: 793-801.

Burke, I. C., C. M. Yonker, W. J. Parton, C. V. Cole, K. Flach, and D. S. Schimel. 1989. "Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils." *Soil Science Society of America Journal* 53: 800-805.

Chaneton, E. J., and R. S. Lavado. 1996. "Soil nutrients and salinity after long-term grazing exclusion in a flooding Pampa grassland." *Journal of Range Management* 49: 182-187.

Charney, J. G. 1975. "Dynamics of deserts and droughts in the Sahel." *Quarterly, Journal of the Royal Meteorological Society* 101: 193-202.

Cole, C. V., I. C. Burke, W. J. Parton, D. S. Schimel, and J. W. B. Stewart. 1989. "Analysis of historical changes in soil fertility and organic matter levels of the North American Great Plains." In: *Proceedings o/ the International Conference on Dryland Farming*, P. W. Unger, T. V. Sneed, and R. W. Jensens, eds., pp. 436-438. College Station: Texas A&M University.

Copeland, J. H., R. A. Pilke, and T. G. F. Kittel. "Potential climatic impacts of vegetation change : A regional modelling study." *Journal of Geophysical Research* (in press).

Dunford, E. G. 1949. "Relation of grazing to runoff and erosion on bunchgrass ranges." *Rocky Mountain Forest and Range and Experimental Station Notes* 7: 1-2.

Elliot, E. T. 1986. "Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils." *Soil Science Society of America Journal* 50: 627-632.

Fankhauser, S., and D. W. Pearce. 1994. "The Social Costs of Greenhouse Gas Emissions." In: *The Economics of Climate Change*, Paris: Organisation for Economic Cooperation and Development—International Energy Agency.

Graetz, D. 1994. "Grasslands." In *Changes in Land Use and Land Cover: A Global Perspective*, W. B. Meyer and B. L. Turner II, eds., pp. 125-147. Cambridge, England: Cambridge University Press.

Hannah, L., J. I.. Carr, and A. Lankerani. 1995. "Human disturbance and natural habitat: A biome level analysis of a global data set." Biodiversity and Conservation 4: 128-155.

Ihori,T., I. C. Burke,W. K. Lauenroth, and D. P. Coffin. 1995. "Effects of cultivation and abandonment on soil organic matter in northeasrern Colorado." *Soil Science Society of America Journal* 59: 1112-1119.

Jones, O. R., H. B. Eck, S. J. Smith, G. A. Coleman, and V. L. Hauser. 1985. "Runoff, soil and nutrient losses from a rangeland and dry-farmed cropland in the Southern High Plains." *Journal of Soil and Water Conscrvation* 40: 161-163.

Kane, S., J. Reilly, and J. Tobey. 1992. "An empirical study of the economic effects of climatic change on world agriculture." *Climatic change* 21: 17-35.

Kattenberg, A., F. Giorgi, H. Grassl, G. A. Meehl, J. F. B. Mitchell, R. J. Stouffer,T.

Tokioka, A. J. Weaver, and T. M. L. Wigley. 1995. "Climate Models-Projections of Future Climate." In *Climate Change: The IPCC Scientifc Assessment,* J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, eds. Cambridge, England: Cambridge University Press.

León, R. J. C., and M. R. Aguiar. 1985. "El deterioro por uso pasturil en estepas herbáceas patagónicas." *Phytocoenologia* 13: 181-196.

Mares, M. A. 1992. "Neotropical mammals and the myth of Amazonian biodiversity." *Science* 225: 976-979.

McNeely, J. A., M. Gadgil, C. Leveque, C. Padoch, and K. Redford. 1995. "Human Influence on Biodiversity." In *Global Biodiversity Assessment,* V. H. Heywood, exec. ed., pp. 715-821. Cambridge, England: Cambridge University Press.

Mitchell, J. F. B., S. Manabe, V. Meleshko, and T. Tokioka. 1990. "Equilibrium Climate Change and its Implications for the Future." In *Climate Change: The IPCC Scientific Assessment* , J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, eds. 135-164. Cambridge, England: Cambridge University Press.

Moraes, J. L., C. C. Cerri, J. M. Melillo, D. Kicklighter, C. Neill, D. L. Skole, and P. A. Steudler. 1995. "Soil carbon stocks of the Brazilian Amazon Basin." *Soil Science Society of America Journal* 59: 244-247.

Mosier, A., D. Schimel, D. Valentine, K. Bronson, and W. J. Parton. 1991. "Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands." *Nature* 350: 330-332.

Nordhaus, W. D. 1991. "To slow or not to slow: The economics of the greenhouse effect." *Economic Journal* 101: 920-937.

Paruelo, J. M., and 0. E. Sala. 1993. "Effect of global change on maize production in the Argentinean pampas." *ClimateResearch* 3: 161-167.

Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. C. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland. 1992. "A comprehensive meterological modeling system-RAMS." *Meteorology and Atmospheric Physics* 49: 69-91.

Pielke, R. A., T. J. Lee, J. H. Copeland, J. L. Eastman, C. L. Ziegler, and C. A. Finley. 1996. "Use of USGS-provided data to improve weather and climate simulations." *Ecological Applications* (in press).

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R Saffouri, and R. Blair. 1995. "Environmental and economic costs of soil erosion and conservation benefits." *Science.* 267: 1117-1123.

Rosenzweig, C., and M. L. Parry. 1994. "Potential impact of climate change on world food supply." *Nature* 367: 133-138.

Running, S. W. 1990. "Estimating Terrestrial Primary Productivity by Combining Remote Sensing and Ecosystem Simulation." In *Remote Sensing of Biosphere Functioning,* R. J. Hobbs and H. A. Mooney eds., pp. 65-86. New York: Springer Verlag.

Sala, **O.** E., M. Oesterheld, R. J. C. León, and A. Soriano. 1986. "Grazing effects upon plant community structure in subhumid grasslands of Argentina." 67: 27-32.

Shantz, H. L. 1954. "The place of grasslands in the earth's cover of vegetation." *Ecology* 35: 142-145.

Shine, K. P., R. G. Derwent, D. J. Wuebbles, and J. J. Morcrette. 1990. "Radiative Forcing of Climate." In *Climate Change: The IPCC Scientific Assessment*, J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, eds., pp. 41-68. Cambridge, England Cambridge University Press.

U.S. Department of Commerce. 1995. *Census Of Agriculture 1992.* Washington, D.C.: Bureau of the Census.

Vavilov, N. I. 1951. The Origin, Variation, Immunity and Breeding of Cultivated Plants. NewYork: Ronald Press.

Wilson, A. T. 1978. "Pioneer agriculture explosion and CO_2 levels in the atmosphere." *Nature* 273: 40-41.