ASSESSMENT OF C BUDGET FOR GRASSLANDS AND DRYLANDS OF THE WORLD

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Abstract. Intergovernmental Panel on Climate Change (IPCC) estimates indicate that potential changes in seasonal rainfall and temperature patterns in central North America and the African Sahel will have a greater impact on biological response (such as plant production and biogeochemical cycling) and feedback to climate than changes in the overall amount of annual rainfall. Simulation of grassland and dryland ecosystem responses to climate and CO_2 changes demonstrates the sensitivity of plant productivity and soil C storage to projected changes in precipitation, temperature and atmospheric CO_2. Using three different land cover projections, changes in C levels in the grassland and dryland regions from 1800 to 1990 were estimated to be -13.2, -25.5 and -14.7 Pg, i.e., a net source of C due to land cover removal resulting from cropland conversion. Projections into the future based on a double-CO_2 climate including climate-driven shifts in biome areas by the year 2040 resulted in a net sink of +5.6, +27.4 and +26.8 Pg, respectively, based upon sustainable grassland management. The increase in C storage resulted mainly from an increase in area for the warm grassland sub-biome, together with increased soil organic matter. Preliminary modeling estimates of soil C losses due to 50 yr of regressive land management in these grassland and dryland ecoregions result in a 11 Pg loss relative to current conditions, and a potential loss of 37 Pg during a 50 yr period relative to sustainable land-use practices, an average source of 0.7 Pg C yr^{-1}. Estimates of the cost of a 20 yr rehabilitation program are 5 to 8 x 10^9 US\$ yr^{-1}, for a C sequestering cost of approximately 10 US\$ per tC.

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1. Introduction: Scope of the Problem

Grasslands and associated savanna and shrublands are clearly vulnerable to climate change. The sensitivity of grasslands to climate change has been documented by observations of past droughts in the semiarid and arid regions (Weaver and Albertson, 1943; Hare, 1977; Schlesinger *et al.*, 1990). Increased human activity has led to degradation of plant production and soil resources in many of these ecosystems leading to desertification in some regions (UNEP, 1991). The continuing pressure on these ecosystems and the projected modifications in regional climate indicate that further degradation of these lands will occur and that there is potential for still greater C losses.

Changes in seasonal rainfall and temperature patterns in central North America and the African Sahel will have a greater impact on biological response and feedback to climate than changes in the overall amount of annual rainfall (Houghton *et al.*, 1990; Ojima *et al.*, 1991). There are several ways in which changing climate and atmospheric CO_2 concentrations may affect grassland and semi-arid ecosystems. Productivity of these ecosystems is directly linked to precipitation (Le Houerou, 1984; Sala *et al.*, 1988; Parton *et al.*, in press), so changes in precipitation amounts will affect plant production. These changes in production can modify soil C storage. The soil C store in these ecosystems is a very important pool, since it represents a significant proportion of the total system C and is stabilized for hundreds to thousands of years.

In the following analysis, several important features of the grassland and dryland region will not be covered in our assessment at this workshop. First, the soil C stored as inorganic constituents in these arid environments is substantial, but the flux rates from the carbonates are relatively small. Second, the paleosols, in certain regions, can also be an important C pool; however, there is no systematic way to deal with the exposure of these soils and subsequent oxidation of their stored C. Third, invasion by or increase in woody species may be significant in grassland communities, and was not included in our climate change simulation. However, this is an indirect effect more closely linked to the frequency and intensity of burning and grazing (Archer, 1993, in press; Schlesinger *et al.*, 1990).

Our considerations will deal with those changes in plant production and decomposition due to global change or to management practices which will impact the level of stored soil C on a time scale of decades to centuries. The following sections will discuss the grassland and dryland ecoregions being considered in this analysis, key ecological and biological issues related to the uptake and storage of C in these ecosystems, estimate the range of the C source or sink of these ecoregions, and discuss the role of mitigation practices that would modify the magnitude of the source or the sink from the different grassland and dryland ecoregions.

2. Key Ecological Considerations for Assessment of Global Change in Grasslands and Drylands

Grasslands by their very nature are resource-limited, particularly for N and water. In the natural grassland ecosystems considered here, essentially all nutrient resources are supplied by the system through nutrient cycling and water through precipitation. The seasonal distribution of rainfall is a major determinant of plant production in many semiarid and arid regions. Simulation of ecosystem responses to climate change in grassland regions of the world demonstrate the sensitivity of soil C storage and grassland biogeochemistry processes to seasonal distribution of precipitation changes and to overall increases in temperature (Ojima *et al.*, 1991). Modifications of resource use efficiency among various grassland and aridland communities are important to projecting how these ecosystems will respond to increased atmospheric CO_2, change in climate, or increases in atmospheric deposition of N.

In addition, these semiarid and arid lands are vulnerable to human-induced land use changes, and these land uses affect soil C storage, soil fertility, soil erosion rates, dust loading into the atmosphere, trace gas exchange, and water and energy balances. The overall impact of these management practices on C storage in grassland and dryland soils are potentially greater than that of climate change or increased atmospheric CO_2 concentrations.

In temperate grasslands, dominated by C_3 species, they are also limited by C due to high photorespiration rates. These resource limitations result in relatively low net primary and secondary productivities, especially in the arid regions. Plants with the C_3 photosynthetic pathway generally have increased C fixation rates when CO_2 levels are increased, while C_4 plants do not increase in C fixation to the degree that C_3 plants do (Kimball, 1983). Photosynthetic capacity of plants with the C_3 pathway is limited by current atmospheric CO_2 levels due to oxygenase activity of ribulose-1,5-bisphosphate carboxylase (Rubisco). Innumerable studies have shown increased C_3 photosynthesis with elevated CO_2 (Newton, 1991). C_4 photosynthesis is not considered C-limited, because C is initially fixed in the mesophyll by phosphoenolpyruvate carboxylase (PEPc) which does not have oxygenase activity (Edwards and Walker, 1983). It appears that the grassland ecosystems dominated by C_4 grasses will likely not experience increased C acquisition as a result of improved photosynthetic capacity (Knapp *et al.*, 1993).

In ecosystems with frequent water stress, enhanced water-use efficiency due to partial stomatal closure in CO_2-enriched environments is likely more important than photosynthetic pathway (Gifford *et al.*, 1990). Morrison (1985) reviewed the literature concerning CO_2 enrichment and water relations and reported a range of 60% to 160% increase in WUE for both C_3 and C_4 plants. For tallgrass prairie, increased above- and belowground biomass production under elevated CO_2 without input of additional water has been reported (Owensby *et al.*, 1993a; Knapp *et al.*, 1993). Owensby *et al.* (1993a) reported increased root production with CO_2

enrichment which would enhance water uptake. Changes in stomatal density may also impart water savings for plants under elevated CO_2. Woodward (1987) indicated that CO_2 enrichment over the past century has likely reduced stomatal density.

Any change in ecosystem function that improves productivity without additional N input will increase N use efficiency (NUE). NUE will almost certainly increase in most N-poor ecosystems under elevated CO_2. In natural grassland ecosystems, increased NUE was reported by Owensby *et al.* (1993b) in a CO_2 enriched tallgrass prairie over a 3-yr period. Reduced N requirement in N-limited systems may increase plant inputs into the soil system. The increased NUE will also result in a lower rate of decomposition due to changes in lower litter quality.

3. Ecoregion Definition and Analytical Methods

3.1. GRASSLAND AND DRYLAND ECOREGION DEFINITION

Grasslands and drylands in this assessment are defined as: Natural grasslands and drylands determined by climate (e.g., an aridity index [the ratio of annual precipitation to potential evaporation] between 0.05 and 0.8). Some savanna grasslands in the tropics are similarly determined by the presence of a short, but intense dry season. This definition, therefore, excludes hyper-arid regions but incorporates both the tropical and temperate grasslands of the world, including the humid savannas and grasslands which are maintained primarily by fire and grazing. However, we exclude two types of grassland areas from this analysis, namely:

* croplands previously converted from grasslands; and
* grass-dominated areas in eco-regions or life zones normally classified as forest. Pastures in both tropical and temperate regions which require large inputs of fertilizers or other intensive management are, therefore, not included in this analysis.

Given this definition of grasslands and drylands, we estimated the areal extent of these regions from the BIOME model developed by Prentice *et al.* (1992). Two other estimates of grasslands and dryland area were made using the UNEP (1991) land cover estimates of arid, semiarid, and subhumid regions of the world, and a separate estimate based on Bailey's (1989) Ecoregion approach used by Ojima *et al.* (1993, this volume). We assessed the given land areas for the various classes (Table 1) defined by UNEP (1991) and by Bailey (1989) and grouped them as best as possible according to the BIOME map (Prentice *et al.*, 1992). Potential grassland and dryland regions were taken to be the pre-industrial areas of grassland and dryland and used to estimate "past land cover" (Table 2). Current grassland and dryland areas were obtained after accounting for conversion of a fraction of the cool

Table 1. Grouping of grassland sub-regions as provided by Prentice *et al.* (1992), UNEP (1991) and Bailey (1989), according to the BIOME model of Prentice *et al.* (1992). Abbreviations: AA arid, SA semi-arid, SH sub-humid.

Prentice *et al.* (1992)	UNEP (1991)	Bailey (1989)
Semi-desert	AA Asia	dry continental
Cool grass and shrub	SA Asia (x 0.577) SA South-America (91 Mha)[1] SH Europe SH North-America (x 0.5)	dry temperate
Warm grass and shrub	AA Europe SA Africa SA Asia (x 0.423)[2] SA Australia SA Europe SA North-America SA South-America (174 Mha)[2] SH Africa SH Asia SH Australia SH North-America (0.5) SH South-America	humid temperate dry savanna savanna humid savanna mediterranean
Hot desert	AA Africa AA Australia AA North-America AA South-America	

[1]Based on Bailey (1989)
[2]Based on Ojima *et al.* (1993, this volume)

and warm grasslands to arable land (Prentice *et al.*, 1992). "Future" grassland and dryland extent was obtained from the 2xCO_2 GFDL CGM climate change estimate of altered land cover area (Cramer and Solomon 1993; in review). In addition we subtracted the fraction of area under cropland estimated for the "current" land cover case (Table 2).

Table 2. Changes in biome areas and carbon pools for grasslands and drylands for past, present and future.

	BIOME AREAS			CARBON POOLS[1]			
BIO-REGION[2]	POTENTIAL	CURRENT	FUTURE	PAST	CURRENT	FUTURE "REGRESSIVE"	FUTURE "SUSTAINABLE"
	M ha			Pg			
SEMI-DESERT	[3]a) 499.5	499.5	298.9	27.620	27.620		15.740 (-11.9)
	b) 626.0	626.0	374.6	34.615	34.615		19.726 (-14.9)
	c) 137.1	137.1	82.0	7.581	7.581	5.2 (-2.38)	4.318 (-3.3)
COOL GRASS/SHRUB	a) 571.3	272.5	121.3	11.642	5.553 (-6.1)[4]		1.789 (-3.7)
	b) 791.0	377.3	167.9	16.120	7.689 (-7.6)		2.477 (-5.2)
	c) 304.0	145.0	86.8	6.195	2.955 (-3.2)	2.26 (-6.95)	1.280 (-1.7)
WARM GRASS/SHRUB	a) 1180.5	1016.4	1460.3	51.258	44.133 (-7.1)		63.725 (+19.6)
	b) 2821.0	2428.9	3489.5	122.493	105.466 (-17.0)		152.282 (+46.8)
	c) 1892.6	1629.5	2341.1	82.178	70.755 (-11.4)	63.00 (-7.75)	102.166 (+31.4)
HOT DESERT	a) 1945.5	1945.5	2004.1	34.336	34.336		35.651 (+1.3)
	b) 934.0	934.0	962.1	16.484	16.484		17.115 (+0.6)
	c) -	-	-	-	-		
TOTAL	a) 4196.8	3733.9	3844.6	124.856	111.642 (-13.2)		116.905 (+5.6)
	b) 5172.0	4366.2	4994.1	189.712	164.254 (-25.5)		191.600 (+27.0)
	c) 2333.7	1911.6	1509.9	95.954	81.291 (-14.7)	70.46 (-10.82)	107.764 (+26.8)

[1]Carbon pools are total soil C to 20 cm depth as modeled using CENTURY (Ojima et al., 1993, this volume). An approximate value for soil C to 1.0 m depth may be obtained by multiplying these values by 3-4. Thus, current grassland and dryland soil carbon (range 96 to 190 Pg; average 119 Pg to a depth of 20 cm) is approximately 417 Pg to a depth of 1.0 m.

[2]Biomes as defined by Prentice et al. (1992).

[3]a) Areas for biomes defined by Prentice et al. 1992.
b) Areas derived from UNEP-based aridity index (UNEP, 1991).
c) Areas derived from Bailey Ecoregions (Bailey 1988).

[4]Values in parentheses indicate net flux in C pools from one period to the next.

3.2. ESTIMATING C STORAGE AND FLUXES RELATIVE TO GLOBAL CHANGE

Carbon storage and flux estimates from grassland and dryland regions were estimated under a prescribed climate change scenario (GFHI, IPCC Report, Houghton *et al.*, 1990) and land cover estimates described previously and given in Table 2. The grassland model of CENTURY (Parton *et al.*, 1987, 1992; Parton *et al.*, in press b), was used for the simulations of aboveground net primary productivity (NPP) and soil organic C (SOC) to a depth of 20 cm for 31 sites across the globe (Ojima *et al.*, 1993b, in press). Results from three sets of simulations were used.

* Current climate scenarios using acceptable land management practices;
* Combined effect of climate change and doubling of atmospheric CO_2 (+CC+CO_2+M) using acceptable or sustainable land management practices; and
* Combined effect of clin.ate change and doubling of atmospheric CO_2 (+CC+CO_2-M) using unacceptable or regressive land management.

We modified the plant production parameters under a 2 x CO_2 climate by changing production relative to potential evapotranspiration (PET) and to N use efficiency (NUE). The magnitude of the effect is to cause a 20% increase in plant production with a change in atmospheric CO_2 concentration from 350 to 700 ppm (Ojima *et al.*, 1993, this volume).

In order to generate the double CO_2 climate, we spatially interpolated GCM grid values of projected 2 x CO_2 climate changes of monthly temperature (T) and precipitation (PPT) for each site based on the GCM output made for the 1990 IPCC report (Kittel, pers. comm., NCAR data retrieval system). We applied these projected monthly values in a linear fashion in a 50 yr ramp (see Ojima *et al.*, 1993, this volume).

4. Regional Ecosystem Modeling

For regional simulations, we selected a representative climate for each site within a region and simulated equilibrium ecosystem levels of soil C and plant production. Climate change simulations for a particular region was based on these representative sites and estimates of climate and CO_2 induced modifications to ecosystem dynamics were applied evenly across the region.

Past soil C pools under grassland were calculated using current soil organic matter content projected over a pre-industrial land use scenario (Table 2). Future soil C pools were calculated using both soil organic matter content occurring for a so-called 'regressive management' future scenario, accounting for removal of 50% of the aboveground biomass during grazed months, and an 'sustainable' scenario using the same moderate grazing and burning regimes specified by Ojima *et al.* (1993; this volume).

4.1. CARBON CHANGES IN THE GRASSLAND AND ARID REGIONS IN THE PAST, PRESENT, AND FUTURE

The results from the "climate change scenario only" (i.e., using only projected changes in monthly rainfall and temperature levels and not CO_2 enhancement effects) indicate that soil C losses occur in all grassland regions (losses range from near 0 to 14% of current soil C levels for the surface 20 cm). Plant production varies according to modifications in rainfall amounts under the altered climate and to altered N mineralization rates. Soil decomposition rates responded most predictably to changes in temperature. CO_2 enhancement effects on plant production and the indirect effects on soil C loss tended to reduce the net impact of climate alterations in most of the regions, and actually resulted in net C sinks in the warm grasslands regions.

Using the sustainable land-management regime, results indicate that changes in soil C levels in the grassland and dryland regions from 1800 to 1990 are losses of -13.2, -25.5 and -14.7 Pg (based on land area estimates of Prentice, UNEP and Bailey, respectively, Table 2). The net loss of soil C is due primarily to land use conversion to cropland. Projections into the future based on a double-CO_2 climate including climate-driven shifts in biome areas by the year 2040 resulted in a net sink of +5.6, +27.4 and +26.8 Pg, respectively, based upon sustainable grassland management. The increase in C storage in this future projection resulted mainly from an increase in area for the warm grassland sub-biome (net increase of 280 M ha due to climate-change induced biome shifts) together with a net increase in soil organic C densities for the sites simulated in this sub-biome (Table 2).

We simulated "regressive" land management by increasing grazing levels from 30% to 50% removal for all of the sites analyzed. The impact of "regressive" land management resulted in a loss of soil C in all regions after 50 yrs (Table 2 "Future - regressive" column). Largest losses were evident in the warm grasslands. The total net loss relative to current condition is 10.8 Pg. When this regressive management is compared to a sustainable management system (i.e., light grazing) the net difference is 37.6 Pg gain of soil C. Modification of land use practices can greatly influence the net flux of soil C, changing grasslands from a source of C to a sink for atmospheric C.

4.2. AN ALTERNATIVE SOURCE/SINK ESTIMATE

Using the logic described by Gifford *et al.* (1990), estimates of annual C sequestration in grassland sinks can be alternatively derived. They hypothesized that given the continuous C exchange between live biomass, soil organic matter pools, and the atmosphere with turnover times in grassland ecosystems from 7 to 10 yr, changes in one pool would eventually be distributed to the other linked pools. Accordingly, they surmised that an increase in atmospheric CO_2 would be accompanied by an increase in C stored in live vegetation, the dead litter, and the soil C. The mechanisms involved are likely increased C fixation due to increased photosynthetic capacity and resource use efficiencies, and decreased decomposition rates. Basic assumptions relevant to C storage in grassland ecosystems include (i) turnover times for plant C are a decade or less; and (ii) changes in C:N ratios of plant biomass may reduce decomposition rates (Gifford *et al.*, 1990).

Calculations based on those of Gifford *et al.* (1990) suggest that the present C flux in grassland soils (estimated at 417 Pg; Table 2), may be a net sink of 0.6 Pg yr^{-1} an upper limit. Owensby (1993; this volume) suggested that additional C storage in grassland soils could be as high as 25 to 30% with CO_2 doubling over the next 50 to 70 yrs, i.e., an annual increase of 0.4 to 0.5%. The grassland sink would be in the range of 1.7 to 1.8 Pg yr^{-1}, a number which we regard as an extreme upper limit. The of 0.6 Pg yr^{-1} sink should be regarded only as an alternative estimate of the upper limit for a possible grassland soil sink. The CENTURY model analysis of global grassland ecosystem sensitivity to climate change and CO_2 enhancement shows that changes in temperature and precipitation may more than offset the additional C storage produced by CO_2 enhancement (see Table 2).

5. Policy Issues

Semiarid and arid regions may be among the more sensitive terrestrial ecosystems with respect to global change effects, resulting in severe degradation of their potential to store C (OIES, 1991). Changes which decrease soil moisture and nutrient availability may result in large declines in both soil C and plant productivity. Under these conditions, human activities leading to desertification of certain ecosystems will be greatly accelerated. In the following section we outline an estimation of the level of C lost and the potential for conserving soil C.

5.1. COST OF SEQUESTERING C THROUGH ANTI-DESERTIFICATION PROGRAMS IN THE GRASSLANDS AND RANGELANDS

The CENTURY model estimates a potential soil C flux to the atmosphere from most grassland regions under scenarios of CO_2 enrichment and climate change. The scenarios assume a sustainable land management strategy with respect to fire and grazing pressure and preservation of native plant types. In contrast to this sustainable land management scenario, UNEP (Dregne *et al.*, 1991) has estimated the extent of current land degradation and the projected rate given minimal anti-desertification measures. It has itemized the costs of a 20 yr program to arrest land degradation and restore already degraded lands (Kassas *et al.*, 1991).

Soil C fluxes are driven in part by net primary productivity on the land surface. Desertification results in reductions in net primary productivity. Hence, it is theoretically possible to calculate the differences in soil C storage between scenarios of sustainable management versus current levels of regressive management projected into the future using the CENTURY model and UNEP data. The cost of anti-desertification measures, divided by the difference in annual C flux rates between the two scenarios yields a theoretical price per tonne of mitigating C losses into the atmosphere by restoring degraded drylands. Before performing the calculations it is necessary to examine some of the underlying assumptions and uncertainties.

5.2. STATUS OF THE GRASSLANDS AND DRYLANDS UNDER PRESENT AND FUTURE MANAGEMENT SCENARIOS

The extent of present land degradation is documented in UNEP (1991). Their data were derived from two global data bases: GLASOD (International Soil Reference and Information Center, Wageningen, an index of soil degradation) and an ICASALS data base (Texas Tech University) on land degradation. The combined data were used to estimate the extent of land degradation in the rangelands of the world (Table 3). UNEP does not quantify percentage reduction in net primary productivity in each degradation class, but from the verbal descriptions we infer that moderate degradation is approximately 25 to 50%, severe 50 to 75% and very severe >75% loss of net primary productivity due to land use practices. At present, 70% of rangelands (3.32 Bha) are at least moderately degraded and UNEP estimates that desertification is increasing at an annual rate of 3.5%, defined by the percentage of the land base passing into a higher-degradation category from case-study data for eight well-studied countries. For the purpose of the calculations, we have assumed that the grazing removal rate is 50% using the site specific grazing management practices projected over 50 yr, compared to 30% removal rate for the sustainable management scenario. Again, we believe this to be a conservative projection from the UNEP data.

Differences in C flux between the two management scenarios were derived from the CENTURY model and are justified separately. They predict that over 50 yr the difference in C emissions between the regressive land use scenario and the progressive or optimal management scenario will be 37 Pg (annual difference = 0.7 Pg) over the whole land base under consideration (4.5 Bha of grasslands and rangelands). This is a significant rate of sequestration (ca. 12% of fossil fuel C emissions). It is important to note that the half-life of the 37 Pg (net) stored soil C is measured in hundreds of years. This is a much longer storage interval than can be achieved with tree plantations, forest preservation, or other sequestration scenarios that depend upon storing C in aboveground standing crop.

Table 3. Extent of desertification in rangelands within the drylands of the world (Dregne *et al.*, 1991).

Mha	Slight-none	Moderate	Severe-moderate	Very Severe	Total
Africa	347	274	716	5.3	995
Asia	384	485	692	10.8	1188
Australia	296	277	55	29.0	361
Europe	31	27	52	1.2	81
N. America	72	116	285	10.2	411
S. America	93	88	184	15.3	288
Total	1223	1267	1984	71.8	3323

5.3. COSTS OF ACHIEVING AN OPTIMUM MANAGEMENT SCENARIO

UNEP has developed a detailed series of regional plans for anti-desertification (Kassas *et al.*, 1991). The programs include afforestation, reforestation, planting of shrubs and grasses, control of grazing lands, planting halophytes on salinized land for animal feed and to sequester C (Glenn *et al.*, 1992), and numerous other remediation methods. Costs depend upon the severity of degradation and the intensity of land use (Table 4).

The urgency of initiating anti-desertification actions can be seen from Table 5 - as desertification proceeds, costs rise dramatically as land passes into higher degradation categories which require greater expense per unit of land. Our present concern is only with the rangelands (non-croplands) in Table 4. Annual costs to restore this land base are in the range 5.0 to 8.8 x 10^9 US$. Divided by the mean annual sequestration rate (i.e., 0.7 Pg per yr^{-1}), the cost per t C is about 10 US$. This estimate is within the range of estimates that have been calculated for forest sequestration schemes. However, as noted below, there are other policy considerations in regard to rehabilitating the drylands.

5.4. COSTS OF NOT CONDUCTING ANTI-DESERTIFICATION IN THE DRYLANDS

UNEP (1991) estimates the average annual income foregone due to degraded rangelands to be 23 x 10^9 US$ yr^{-1}. They calculate the cost:benefit ratio of restoring the rangelands as 1:3.5 on a global basis. However, the large sums of money required for investment in restoration have not been generally made available

Table 4. Global costs in 10^9 US$ for a 20 yr program of direct anti-desertification measures (UNEP, 1991).

	Cropland			
	Irrigated	Rain-fed	Rangelands	Cost yr^{-1}
Preventive measures	10-31	12-36	6-18	0.3-.9
Corrective measures	17-50	18-55	13-38	0.7-1.9
Rehabilitation measures	21-41	22-59	80-120	4-6
Total			99-176	5-8.8

Table 5. Global average indicative costs for direct antidesertification measures in different land use systems (US$) (UNEP, 1991).

Extent of Degradation	Cost of Restoration	US$ ha^{-1}	
Slight/None	100-300	50-150	5-15
Moderate	500-1500	100-300	10-30
Severe	2000-4000	500-1500	40-60
Very Severe	3000-5000	2000-4000	30-70

(Kassas *et al.*, 1991). The funds required for restoration are available internally for the industrialized regions (N. America and Australia) and the oil-producing regions (the Middle East), but the developing countries in arid zones of Africa and Asia will require external support to conduct anti-desertification on a meaningful scale. The failure of past anti-desertification programs in these regions has been attributed directly to lack of funding (UNEP, 1991).

5.5. OTHER POLICY CONSIDERATIONS

The question of social equity needs to be considered. Should development and environmental projects be judged primarily on their net ability to sequester C in the future? If a massive transfer of payments from industrialized to developing countries for the purpose of C offsets occurs, will the decisions be based solely on storing the most C at the lowest price, even if there are no social benefits, or will priority be given to schemes which are necessary even in the absence of global warming?

A major concern is whether anti-desertification measures, even if fully funded, can be effective. Technical solutions to rehabilitating rangelands are available but if population increases put additional pressure on the landscape, desertification may continue despite external funding for anti-desertification programs.

6. Research Perspective

A number of research needs were identified at the workshop that would alleviate gaps in our current knowledge of grasslands and dryland ecosystems responses to changing atmospheric CO_2 and climate conditions. These research needs include:

Ecophysiology and Ecosystem Science - Response of natural ecosystems, above and below ground, across broad climate gradients to elevated CO_2 with particular emphasis on changes in relationships among environmental variables such as temperature, moisture, and nutrients. In mixed C_3-C_4 ecosystems, determination of differential responses among species that affect productivity and interspecific competition leading to composition shifts. Particular emphasis should be placed on carbon pool quantification over time and space for selected ecosystems.

Land Use Management - Response of natural ecosystems to elevated CO_2 under traditional and anticipated management, including sustainable, rehabilitative, and regressive strategies utilizing, for example, grazing, fire, and conversion strategies.

Modeling of Ecosystem and Ecophysiological Responses - Using data obtained from the ecophysiology and management research, models should simulate responses across all scales. Modeling efforts are currently constrained by inadequate databases of ecosystem responses to elevated CO_2 for essentially all ecosystems. In addition, collaboration with development and application of data bases that include land cover, land use, and soils. This would facilitate projections of future scenarios for assessment purposes.

Monitoring and Coordination of Research Efforts - Long-term assessments of grassland and dryland ecosystem productivity, above and below ground, in response to year-on-year variation in climate (temperature, precipitation, etc.), concentrated at a series of study sites covering the whole range of these ecosystems. These measurements should be combined with more extensive monitoring over large areas using techniques such as satellite and aircraft remote sensing. Research efforts at all sites should be coordinated to provide relatively uniform data collection and synthesis methodologies required to produce databases for efficient distribution to varied uses.

7. Summary

The potential effects of management on carbon storage in grassland and dryland soils are substantially greater than that of climate change or CO_2 enhancement. Projections into the future based on a double-CO_2 climate including climate-driven shifts in biome and accounting for cropland areas by the year 2040 resulted in a net C sink ranging from +5.6 Gt to +27.4 Gt, for three different land cover projections respectively, based upon optimal grassland management. The increase in C storage in this future projection resulted mainly from an increase in area for the warm grassland sub-biome (net increase of 280 M ha due to climate-change induced biome shifts) together with a net increase soil organic C density resulting from net ecosystem response to climate changes and enhanced CO2 concentrations.

Differences in C flux between sustainable and regressive management scenarios were derived from the CENTURY model and are justified separately. They predict that over 50 yr the difference in carbon emissions between the regressive scenario and the sustainable management scenario will be 37 Gt (annual difference = 0.7 Gt) over the whole land base under consideration (4.5 B ha of grasslands and rangelands). The cost per t C is around US$10. This estimate is within the range of estimates that have been calculated for forest sequestration schemes.

The soil store of C in these ecosystems is a very important pool, since it is stabilized for hundreds to thousands of years, and forms the bulk of the grassland C pool. Calculations based on those of Gifford *et al.* (1990) suggest that the present C pool in grassland soils (estimated at 417 Gt; Table 2), may be a net sink of 0.6 Gt per annum.

8. References

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