Impact of Carbon Storage Through Restoration of Drylands on the Global Carbon Cycle

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ABSTRACT / We evaluate the potential for global carbon storage in drylands as one of several policy options to reduce buildup of carbon dioxide in the atmosphere. We use the GLOCO model, a global carbon cycle model with eight terrestrial biomes that are described mechanistically in detail in terms of the biological processes that involve carbon and nitrogen cycling and the effect of temperature on these processes. GLOCO also considers low-latitude and high-latitude oceans, each divided further into a surface layer and several deeper layers, with an explicit description of biogeochemical processes occurring in each layer, and exchanges among ocean reservoirs and the atmosphere. GLOCO is used to study the transient response of actual vegetation, which is more realistic than looking at equilibrium conditions of potential vegetation.

Using estimates of land suitable for restoration in woodlands, grasslands, and deserts, as well as estimates of the rate at which restoration can proceed, we estimate that carbon storage in these biomes can range up to 0.8 billion tons of carbon per year (Gt C/yr), for a combination of land management strategies. This corresponds to a reduction in atmospheric buildup of 0.5 Gt C/yr, which represents up to 15% of the average annual atmospheric carbon buildup in the next century, 3.5 Gt C/yr, assuming the IPCC 32d scenario. A global strategy for reducing atmospheric carbon dioxide concentration will require the implementation of multiple options. The advantage of carbon storage in restored drylands is that it comes as a side benefit to programs that are also justifiable in terms of land management.

The increase in atmospheric carbon dioxide buildup is well recorded both by direct measurements, most notably the Mauna Loa record, and indirect measurements dating back many decades, e.g., the Siple ice core data (Keeling and others 1989). Whether this rise in atmospheric carbon dioxide will result in global climate change will be debated for many years to come, as will the positive or negative effects that such changes may have on human activities and terrestrial vegetation. Nevertheless, it is important to identify options to reduce the rate of atmospheric carbon increase. No single option will probably be sufficient by itself to significantly reduce the rate of increase.

Careless management of woodlands, grasslands, and arid areas has resulted in significant degradation of vegetation cover and soil quality, leading in many cases to desertification. Associated with these activities is a net carbon loss from terrestrial biomes and soils to the atmosphere. Concurrently the burning of fossil fuels in heavily industrialized nations, and the conversion of natural biomes to pastures and other agricultural uses results in a large flux of carbon to the atmosphere, which only after a long time partially redistributes to the oceans and the remaining natural biomes. Several "management" options have been proposed to reduce the buildup of carbon dioxide in the atmosphere and reduce the likelihood of changes in global climate, including reduction of fossil fuel burning and degradative land use changes, storage of carbon in the oceans, etc.

There are some actions that may be taken at no cost or relatively low cost that will reduce the average per capita use of energy, for example efficiency gains in electricity, oil, and gas use in residential, commercial, and industrial sectors (Rubin and others 1992). Other actions under study involve the long-term storage of fossil fuel emissions in the deep ocean (Keller and Goldstein 1995, Kheshgi and others 1994, Golomb and others 1992, Marchetti 1977). It is also likely that the natural biomes (forests, grasslands, woodlands, tundra, and deserts) are already participating in additional storage of a fraction of the carbon from fossil fuel combustion, although physical evidence for this is scant.
Actions that can be taken to accelerate storage of carbon in the terrestrial biosphere may be done at relatively low cost and thus may partially offset some of the emissions from fossil fuel burning.

One option is to use the potential for terrestrial carbon storage available through restoration of degraded drylands and desert fringes to their original carbon content, or in some cases even increase the carbon storage capacity if economically feasible. This alternative has the advantage of sharing the cost of carbon storage with the land’s restoration, providing multiple benefits. Concurrent actions to reduce carbon buildup in the atmosphere are the activities undertaken by the United Nations Environmental Programme (UNEP) and individual nations to combat desertification and to restore the ecological quality of their drylands (UNEP 1992). Indirectly, these activities may result in storage of a fraction of carbon emissions and thus share the overall cost of both restoring drylands and reducing atmospheric carbon. Joint implementation programs may be designed between countries emitting large amounts of carbon to the atmosphere and those needing funds to combat desertification, to partially offset the emissions. Intragional offsetting of fossil fuel emissions is possible by combining projects between local power-generating utilities and land management agencies.

This work’s objective is to use a global carbon cycle model, GLOCO version 2, to analyze the potential for storage of carbon in drylands. First, we provide a brief description of the model, followed by a response analysis to different management options that increase the storage of carbon in drylands. Then we estimate the extent of degradation of the drylands to formulate a future scenario for management actions. These actions are then studied individually and in combination using GLOCO, to determine a realistic range for carbon storage in drylands.

GLOCO Model

The GLOCO model was developed by Hudson and others (1994) for the Electric Power Research Institute (EPRI) to evaluate management options to reduce the rate of carbon buildup in the atmosphere with a dynamic model that could represent the interactions between the global carbon and nitrogen cycles, with biogeochemical processes, and with various carbon and nitrogen emissions scenarios, including industrial, agricultural, and forestry activities. GLOCO version 2 (Hudson and others 1995), comprises eight terrestrial biomes, linked through a well-mixed atmosphere with low-latitude and high-latitude oceans. The oceans are further described by surface and deep subcompartments. The oceanic model is based on the HILDA model of Siegenthaler and Joos (1992), which has been calibrated using the isotopic carbon tracers 13C and 14C. The GLOCO v2 model was calibrated by Hudson and others (1994) using historical atmospheric CO2 concentrations, as well as the Geochemical Ocean Sections Study (GEOSECS, from Takahashi and others 1981a,b) oceanic profiles of dissolved organic carbon, alkalinity, and phosphate.

The model allows the user to input all the parameter values governing all biome processes (e.g., net primary productivity, litterfall, carbon-to-nitrogen ratios in the various tissues, etc.), ocean processes (e.g., biological uptake of carbon, convection and dispersion of carbon within a layer and to other layers, etc.), and atmospheric processes (e.g., gas-water exchange, methane oxidation to carbon dioxide), as well as the relationship between temperature and atmospheric CO2 for each biome and ocean. Additional inputs to GLOCO include historical and future anthropogenic activities affecting the global carbon cycle, such as fossil fuel emissions (as carbon dioxide and as methane), anthropogenic nitrogen emissions and deposition rates in different biomes, land-use changes either from a natural biome to an agricultural biome or reverting agricultural land to the original biome (which requires time to allow the vegetation to grow back), and shifting cultivation.

The model provides as outputs carbon dioxide and methane concentrations in the atmosphere, projected temperatures in each biome and ocean, oceanic inorganic and organic carbon concentrations and alkalinity, changes in carbon and nitrogen stocks in each terrestrial biome subcompartment (e.g., wood, litter, soil organic matter, etc.), and the land area in each biome, as well as an overall carbon mass balance for each biome, ocean, and atmosphere.

The eight terrestrial biomes considered in GLOCO are: temperate grasslands, woodlands, desert, tundra, temperate forest, tropical forest, boreal forest, and an agricultural biome, which is actually broken down into seven subbiomes depending on the vegetation prior to cultivation. The Whittaker and Likens (1973) ecosystem types were aggregated by Hudson and others (1994) on the basis of carbon pool sizes and net primary production (NPP); for this study, it is important to note that the woodland biome comprises tropical and temperate woodlands, shrublands, and savannas.

The terrestrial biomes are all modeled based on a generic biome. The main carbon reservoirs in each biome are foliage stem, roots, litter, soil organic matter (SOM), and humus. In each biome subcompartment
there is a balance between carbon and nitrogen determined by carbon-to-nitrogen ratios (C:N) which can be modified by the user. Both carbon and nitrogen from anthropogenic activities participate in the fertilization of the biomes, and both nutrients are lost through rivers to the oceans due to weathering and leaching. Different nitrogen deposition, fixation, and leaching rates can be specified for each biome.

The main processes in each biome are presented in Table 1, along with the main variables in each process. Most processes are temperature dependent, and some are limited by nitrogen or carbon availability or the ratio of these nutrients. While some processes are first order, others represent more complex behavior (e.g., gross primary productivity) that depends nonlinearly on CO$_2$ concentration. Each biome is calibrated independently to achieve an equilibrium condition under no external forcing, and then the parameter values are transferred to the full GLOCO model.

### Response Analysis

There are three main options in GLOCO for modeling drylands management that result in carbon storage: (1) restoring degraded pasture and agricultural land to its original biome (either woodland or grassland); (2) increasing the net ecosystem productivity (NEP) of the degraded biome; (3) increasing the production of SOM in the portion of agricultural and pastoral land that corresponds to either woodlands or grasslands.

In all cases, the GLOCO simulations are run for 100 years to evaluate the effects of each land management strategy, and then the resulting carbon storage or loss is converted to an average annual basis. Initial conditions are based on 1990 estimates of carbon and nitrogen stocks and biome areas. A background emissions scenario for fossil fuel combustion of 6 Gt C/yr is imposed on all simulations. Woodland and grassland biomes are relatively insensitive to carbon fertilization (Keller and Goldstein 1994); in the event that the actual level of fossil fuel emissions varies compared to the simulated 6 Gt C/yr, the results presented here would not be affected significantly. The effects of the carbon fertilization effect are subtracted from the response to each land management strategy, by comparing against a base case with no management actions.

Converting degraded pasture and agricultural land to woodlands or grasslands at different annual rates results in a net annual storage in the terrestrial biosphere of about 0.03 Gt C/yr per Mha/yr converted, based on GLOCO model output, with little difference whether the original biome is a woodland or a grassland (Figure 1). The increase in carbon storage is essentially linear with increasing land-use change to the original biome. The response of the drylands to land-use changes is considerably smaller than the response of the temperate, boreal, or tropical forests in terms of net annual carbon uptake, which ranges from 0.09 to 0.14 Gt C/yr per Mha/yr converted, based on GLOCO output. The model assumes that the agricultural land is reverted to its original biome (i.e., grassland cannot be converted first to agriculture or pasture and then to woodland). However, if the agricultural land is simply abandoned, it may result in additional soil erosion and possibly desertification (Garcia-Ruiz and others 1994), suggesting that reverting agricultural land to its original biome may require at least some management. In GLOCO's aggregated description, we do not consider the particular characteristics of spatial organization of dryland vegetation, with patches of relatively dense vegetation near water supply and the rest of the territory covered only sparsely with open shrubs; considering this spatial

### Table 1. Main terrestrial biome processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Main variables</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosynthesis</td>
<td>$P_{CO_2}$, $T$</td>
<td>Carbon in tissue</td>
</tr>
<tr>
<td>Respiration</td>
<td>$T$</td>
<td>CN ratio in tissue, $[N]_{soil}$, $T$</td>
</tr>
<tr>
<td>Nitrogen Uptake</td>
<td>$C_{GOMO}$, $[N]_{soil}$</td>
<td>Constant partitioning</td>
</tr>
<tr>
<td>Litterfall</td>
<td>$T$</td>
<td>Carbon in tissue</td>
</tr>
<tr>
<td>Humus Mineralization</td>
<td>$T$, $[N]_{soil}$</td>
<td>User-specified rate</td>
</tr>
<tr>
<td>CH$_4$ Emissions</td>
<td>$T$, $[N]_{soil}$</td>
<td>Natural and anthropogenic rates</td>
</tr>
<tr>
<td>Nitrogen Deposition</td>
<td>$T$</td>
<td>$[N]_{soil}$</td>
</tr>
<tr>
<td>Nitrogen Leaching</td>
<td>$T$, $[N]_{soil}$</td>
<td>$T$</td>
</tr>
<tr>
<td>Nitrogen Fixation</td>
<td>$T$</td>
<td>$T$</td>
</tr>
<tr>
<td>Carbon loss due to</td>
<td>$T$, $[N]_{soil}$</td>
<td>$T$</td>
</tr>
<tr>
<td>Weathering</td>
<td>TOC export rate</td>
<td>$P_{CO_2}$ atmospheric CO$<em>2$ concentration, $T$ temperature in biome, CN, carbon-nitrogen ratio $[N]</em>{soil}$, nitrogen concentration in soil $C_{GOMO}$, carbon in soil organic matter, $T$ soil total organic carbon.</td>
</tr>
</tbody>
</table>

* $P_{CO_2}$ atmospheric CO$_2$ concentration; $T$ temperature in biome; $C_{GOMO}$ carbon-nitrogen ratio $[N]_{soil}$, nitrogen concentration in soil $C_{GOMO}$, carbon in soil organic matter; and TOC, total organic carbon.

**Figure 1.** Average annual carbon storage in the terrestrial biome upon restoration of degraded pasture and agricultural land to the original dryland biomes as a function of the rate of land use change.
distribution may affect the potential increase in carbon storage.

The actual reduction in atmospheric carbon buildup is about 60% of the rate of storage in the biosphere due to partitioning of carbon among oceans and other natural biomes, for an annualized decrease in the atmospheric carbon buildup of about 0.02 Gt C/yr per Mha/yr converted. For example, if 5 Mha of agriculture is converted every year to woodlands, with a total conversion of 500 Mha after 100 years, the carbon stored in the terrestrial biome is 15 Gt C, and the decrease in carbon buildup in the atmosphere is about 10 Gt C.

A second management policy is to increase the average NEP of woodland and grassland biomes. Increases in NEP may be achieved by woodland forest and fire management (Singh 1994, Lonsdale and Braithwaite 1991), control of overgrazing (Owens and others 1983, Sundriyal and Joshi 1990), introduction of plant species with greater NPP (Esser 1992), tree planting (Ahlback 1994, Nair 1984), halophyte crops in soils with high salinity (Douglas 1993), and actions to raise the productivity of arid lands by restoring the quality of the soils and/or the vegetation cover in drylands that have been overgrazed or farmed intensively (Skoupy 1993) or where erosion and salinization processes have impoverished the soil (Dregne 1990, Szabo 1992, 1989, Crosson and Stout 1983). Small-, medium-, and large-scale projects have been undertaken in South America (Mendoza 1998), North America (Hunt 1986), the Middle East (Omar and Abdal 1994), Africa (Darkoh 1989), India (Sinha 1993), and China (Zhenda and Tao 1993), to name just a few examples.

In the GLOCO model, NEP can be modified by adjusting the maximum net photosynthesis ($N_{P_{\text{max}}}$) per unit area, which determines gross photosynthesis ($GP$), and thus NEP as follows (Kohlmaier and others 1988, Hudson and others 1995):

$$GP = GP_{\text{max}} N_{I} \frac{P_{\text{CO}_2}}{P_{\text{CO}_2} + K_{\text{CO}_2}} \Delta t$$

where

$$GP_{\text{max}} = N_{P_{\text{max}}} \cdot \text{TEMP} + k_{\text{RES}} \cdot S_{I} \cdot Q_{T_{10}}^{T_{10}}$$

and $N_{I}$ is the net annual allocation of nitrogen to production of foliar tissue, $P_{\text{CO}_2}$ is the partial pressure of CO$_2$ in the atmosphere, $K_{\text{CO}_2}$ is the half-saturation constant for CO$_2$ uptake, $\Delta t$ is the unit time step, $S_{I}$ is the carbon-to-nitrogen ratio at seasonal maximum foliage, $k_{\text{RES}}$ is the foliar respiration rate constant at 0°C, $Q_{T_{10}}^{T_{10}}$ is the temperature sensitivity function for foliar respiration

$$\text{TEMP} = \max \left[ \frac{(T - T_{\text{min}}) (T - T_{\text{max}})}{(T - T_{\text{min}}) (T - T_{\text{max}}) - (T - T_{\text{opt}})^2} , 0 \right]$$

$T$ is the actual temperature in the biome, $T_{\text{opt}}$ is the optimal temperature for ecosystem function (for each biome), $T_{\text{min}}$ is the minimum temperature for ecosystem function (for each biome), and $T_{\text{max}}$ is the maximum temperature for ecosystem function (for each biome).

$GP$ in each biome must also equal the sum of all carbon allocated to each plant tissue:

$$GP = \sum [\Delta C_{I} \cdot (1 + x_{I}) + k_{\text{RES}} \cdot S_{I} \cdot Q_{T_{10}}^{T_{10}} \cdot \Delta t]$$

where $\Delta C_{I}$ is the net annual allocation of carbon to production of tissue, $x_{I}$ is the ratio of growth respiration to carbon allocated for new growth of tissue, and $C_{I}$ is the carbon in $I$th reservoir.

Although the rate of decomposition, $D_{I}$, of the $I$th soil component (GLOCO considers litter, soil organic matter, and humus as three distinct reservoirs in each biome, with different parameter values and carbon and nitrogen stocks) is not modified, it is a function of available carbon, nitrogen and temperature, and thus will be affected by the increase in $N_{P_{\text{max}}}$ as well as other environmental changes:

$$D_{I} = k_{D_{I}} \cdot C_{I} \cdot \frac{N_{\text{avg}}}{(K_{D_{I}} + N_{\text{avg}})} \cdot Q_{T_{10}}^{T_{10}} \cdot \Delta t$$

where $k_{D_{I}}$ is the rate constant for decay of $I$th soil component, $C_{I}$ is the carbon stored in $I$th soil component, $N_{\text{avg}}$ is the available nitrogen, $K_{D_{I}}$ is the half-saturation constant for nitrogen uptake, and $Q_{T_{10}}^{T_{10}}$ is the temperature sensitivity function for soil decay.

Figure 2 presents the response analysis of four biomes to an increase in average $N_{P_{\text{max}}}$. The largest
response is obtained from woodlands, where a 10% increase in average \( NP_{\text{max}} \) results in an annualized change in carbon storage in the woodlands biome of 0.2 Gt C/yr. There is a net storage of about 20 Gt C in 100 years. The average net primary productivity of woodlands considered in GLOCO is 20% less than for grasslands (0.319 vs 0.404 kg C/m²/yr), but with a larger biome area (3125 Mha vs 2051 Mha for grasslands) and a higher fraction of carbon allocated to woody tissue in woodlands, the net increase in carbon stocks is significantly higher.

The corresponding decrease in atmospheric carbon buildup is 0.09 Gt C/yr for a 10% increase in \( NP_{\text{max}} \) in the woodlands biome, assuming no land-use changes during the 100-yr simulations. The response of grasslands is almost identical to the desert biome, with only about 0.04 Gt C stored per year in each biome for an average 10% increase in \( NP_{\text{max}} \). Deserts in the GLOCO model correspond to hyperarid lands, with an aridity index (actual precipitation over potential evapotranspiration ratio) of less than 0.05. The tundra biome has a negligible response to an increase in \( NP_{\text{max}} \).

There are significant differences in carbon storage per unit area in the various biome carbon reservoirs due to an increase in \( NP_{\text{max}} \). GLOCO predicts that grasslands store most of the additional carbon as litter (Figure 3) or SOM, whereas woodlands store most of the additional carbon as wood (Figure 4), with some increase in litter and SOM. Note the large difference in scales.

The third analysis involves the increase of SOM production in the fraction of the woodland or grassland biomes that has been converted to agriculture or pasture, by introducing deep-rooted grasses (Fisher and others 1994). An analysis of factors affecting SOM to improve soil management (Porton and others 1987), and promoting nitrogen fixation in dryland soils (Giller and Cadisch 1995; Hardarson 1995, Sprent and others 1988). Agricultural SOM is modeled in GLOCO as a function of biome temperature, with an atmospheric CO₂ and nitrogen fertilization effect:

\[
P_{\text{SOM}} = P_{\text{SOM, max}} \cdot \frac{P_{\text{CO₂}}}{K_{\text{CO₂}} + P_{\text{CO₂}}} \cdot \frac{N_{\text{N}}}{(K_{\text{N}} + N_{\text{N}})} \cdot Q_{\text{Tsol}}^{1/3} \cdot \Delta T
\]

SOM decomposition will increase since it is a function of carbon and available nitrogen. An increase of 10% in maximum SOM production (\( P_{\text{SOM, max}} \)) in the agricultural or pastoral portion of either of these biomes results in an annual average net increase in carbon storage of 0.04–0.06 Gt C/yr (Figure 5). Converted grasslands are more sensitive to an increase in SOM production due to their larger area (about 400 Mha of grasslands converted to pasture or agriculture vs 360 Mha for woodlands, since 1700) and lower SOM decom-
position rates given a lower global mean annual temperature in grasslands. The corresponding reduction in atmospheric carbon is 0.02-0.03 Gt C/yr for a 10% increase in SOM production.

**Historical Land-Use Changes and Carbon Loss**

Figure 6 presents the historical change in land use as compiled by Hudson and others (1994) from several sources (Houghton and Hackler 1994, Houghton 1991a,b; Houghton and others 1988, 1991a,b). The total terrestrial biome area, 12,800 Mha, is conserved from 1700 to 1990. The rapid increase in the agricultural biome is the result of the combined conversion from the natural biomes, in particular the temperate forests in the 1700s and 1800s and the woodlands, grasslands, and tropical forests in recent decades. Some agricultural land in the temperate forest region has been abandoned or actively converted to temperate forest from 1950 on, resulting in a slight increase in the area of this biome in recent decades.

The net change from 1700 to 1990 in terrestrial carbon storage has been calculated using the GLOCO model (Figure 7). The simulation considers emissions from fossil fuel combustion based on the estimates of Keeling (1991) and Marland and Boden (1991). The terrestrial biosphere has lost almost 100 Gt C in these 290 years, which is the net from gains in agriculture and losses in most of the natural biomes, notably the tropical and temperate forests, as well as the grasslands and woodlands. Net terrestrial carbon loss is less than carbon loss due to land-use changes, since there is a significant carbon and nitrogen fertilization effect in the temperate and boreal forests, as calculated by the model. This simulation does not include land degradation after the land-use change.

With respect to drylands degradation, it is estimated (Dregne and others 1991) that of the approximately 5160 Mha of drylands (which excludes the hyper-arid deserts), 69% has been degraded, mainly by the loss of vegetation cover, but in a significant fraction also accompanied by soil degradation, mainly erosion. The fraction of drylands degraded is shown on Figure 8, differentiated according to their major land use. Range-lands exhibit a high level of degradation, around 73%, mostly due to overgrazing, irrigated and rain-fed croplands have fared slightly better, with 50% and 47% degradation of their corresponding areas. Most of the degradation in this case is due to salinization, alkalization, waterlogging, and impoverishment due to lack of crop rotation. Some of these lands have also been lost due to urbanization and are being replaced by using the best rangelands for cultivation. Unfortunately, there has been no comprehensive assessment of the amount of carbon lost due strictly to degradation.
Degradation has been classified from moderate to very severe (Figure 9), indicating a significant biomass loss, above ground and below ground, as well as significant soil degradation (Dregne and others 1991). The level of degradation is highest in North America (85%) and lowest in Australia (55%). The potential land available for restoration and carbon storage is on the order of 3500 Mha.

Future Scenarios for Carbon Storage

Based on the degraded drylands area and the extent of degradation, it is reasonable to assume that actions to combat desertification can indeed increase the average NEP of the woodland and grassland biomes, as well as the SOM production in the agricultural area (irrigated and rain-fed cropland) converted from these biomes. Converting some pastoral and agricultural land back to its original biome may be complicated by increasing population and land-use pressure, but there are many regions where this land has been used only marginally due to its level of degradation and is available for restoration.

Four scenarios are assumed: (1) 8 Mha of degraded agricultural or pastoral land are abandoned yearly and revert to 5 Mha of woodlands and 3 Mha of grasslands; (2) \( N_{p_{\text{max}}} \) of woodlands and grasslands is increased by 10%; (3) average SOM production in the agricultural component of these biomes is increased by 25%; and (4) all three actions are combined, to estimate an upper bound for annual carbon storage in drylands.

The simulations are performed considering the Intergovernmental Panel on Climate Change (IPCC) 92d fossil fuel emissions scenario (IPCC 1992) from 1990 to 2100, which assumes continuing growth of carbon emissions but with some policy actions taken to reduce the rate of growth of emissions. This will result in some terrestrial carbon fertilization, according to GLOCO. In addition, land-use changes in other biomes are not considered, to reduce the complexity of the analysis. Land-use changes in other biomes could be simulated, but the net carbon emissions will probably be only a small fraction of the fossil fuel emissions, providing only a small additional carbon fertilization. Finally, since temperature is an important factor in most biome processes, it is assumed that the average net global increase in temperature is around 3°C/CO\(_2\) doubling; specifically for the woodlands the estimated increase is 2°C/CO\(_2\) doubling, and for the grasslands it is 4.8°C/CO\(_2\) doubling (Harvey 1989). The largest increase in temperature predicted by most global climate models is in the higher latitudes, and we have considered this in the model according to the geographic distribution of the terrestrial biomes.

The effect of the IPCC 92d scenario alone is to increase the terrestrial biosphere storage of carbon by 283 Gt C (Figure 10), considering carbon and nitrogen fertilization and the effect of increasing temperature. Atmospheric carbon is predicted to rise by 375 Gt C, or approximately 3.4 Gt C/yr. In terms of the three biomes of interest, the grasslands biome is predicted to store an additional 51 Gt C, whereas the carbon storage in the woodlands biome and in agriculture is practically unchanged (Figure 11).

The abandonment of agricultural land (land-use changes in Figures 10 and 11) results in an additional 45 Gt C stored in the terrestrial biosphere, or about 0.05 Gt C/Mha reverted. The rate of carbon stored per unit area is greater than was obtained in the response analysis due to the higher carbon fertilization of grasslands, as well as a larger temperature increase, since the IPCC 92d scenario results in a higher atmospheric CO\(_2\) concentration. The increase is largest in grasslands, for a net increase of 61 Gt C over the IPCC 92d scenario. Woodlands gain 56 Gt C. These gains are partially compensated by the loss of carbon in the agricultural
Figure 11. Carbon stored in agriculture, grasslands, and woodlands for the future scenarios. Note that GLOCO predicts that a significant fraction of the IPCC 92d fossil fuel emissions is stored in the temperate, boreal, and tropical forests, as well as in the oceans (not shown).

biome of 65 Gt C. Due to increased carbon storage in drylands, the carbon fertilization effect in temperate, tropical, and boreal forests is diminished by about 7 Gt C. The actual increase in atmospheric carbon is only 343 Gt C, or 32 Gt C less than the IPCC 92d scenario with no land-use changes, as seen in Figure 10. This translates to an average reduction of 0.29 Gt C/yr in the rate of atmospheric carbon buildup.

If the $N_{fmax}$ of woodlands and grasslands is increased by 10%, with no land-use changes, the additional carbon stored in the terrestrial biosphere, relative to IPCC 92d, is 21 Gt C, or 0.19 Gt C/yr. Most of the gain is in woodlands (90 Gt C) with minor additional carbon stored in the grasslands (3 Gt C). The resulting effect is to decrease atmospheric carbon buildup by 13 Gt C, compared to the IPCC 92d scenario, for an average reduction in the rate of atmospheric carbon buildup of 0.11 Gt C/yr.

A 25% increase in agricultural SOM production in the drylands region results in an increase of 23 Gt C stored in the terrestrial biosphere or 0.21 Gt C/yr. The atmospheric increase is 14 Gt C less than the IPCC 92d scenario with no land-use changes, for an average reduction of atmospheric carbon buildup of 0.12 Gt C/yr.

The combination of all three strategies, land-use change through abandonment of agriculture, increasing $NP_{max}$ by 10%, and agricultural SOM by 25%, coupled with the IPCC 92d emissions results in a total increase in terrestrial biosphere carbon of 369 Gt C, a net increase of 86 Gt C compared to the base case. The combined increase in biome carbon storage is 0.78 Gt C/yr. Atmospheric carbon increases by 519 Gt C, or a net reduction from the IPCC 92d (with no land-use changes) of 56 Gt C. The annualized decrease in carbon buildup in the atmosphere is on the order of 0.5 Gt C/yr. Figure 12 summarizes the change in annual carbon storage in the terrestrial biomes and the reduction in atmospheric carbon buildup for the various scenarios relative to IPCC 92d.

Discussion and Conclusions

The GLOCO model has been applied to explore the response of woodland and grassland biomes, which comprise most drylands, to various land management actions that result in carbon storage. The model is particularly suitable for this type of analysis since it is designed to study land-use changes, the effect of carbon and nitrogen fertilization, the changing climate (temperature), and the role that the various biome process parameters play on the global carbon cycle. In addition, since GLOCO couples the terrestrial and the oceanic models through the atmospheric model, it provides a dynamic response of all the components of the global carbon cycle to carbon emissions and land-use changes, which could not be captured in a model only contemplating the terrestrial biosphere. The model does not consider the transient effects of climatic change on migration of species and other changes in ecosystems that may occur during the simulated period. GLOCO has a high level of biome aggregation, and thus the output should be considered as indicative of trends in carbon storage.

With over 3500 Mha of drylands degraded (27% of the terrestrial biosphere), the potential for storing additional carbon as biomass in these regions is significant. Actions taken to increase NEP in these biomes may result in storage of 0.2 Gt C/yr. Increasing SOM production in agricultural drylands may store an additional 0.2 Gt C/yr, and restoring marginal agricultural land to its original natural state can result in the storage of an additional 0.2–0.45 Gt C/yr in these biomes, for a
total terrestrial biome storage of up to 0.8 Gt C/yr. This corresponds to a net decrease in atmospheric carbon buildup of 0.5 Gt C/yr. Given the uncertainties in many parameters in the model, the high level of biome aggregation, and the difficulty in scaling field-level results (of increases in NEP and SOM) to global scales, the results from the GLOCO simulations are only indicative of the potential for carbon sequestration, with a potentially large uncertainty.

The rate of abandonment of agricultural land used in our estimation of an upper bound for carbon sequestration in drylands is in the high range (although not unreasonable for degraded pastoral land) and could not be sustained for a prolonged period without affecting food production. At 8 Mha/yr, it would take slightly more than 200 years to eliminate all of the world’s croplands. It may be argued that there are more efficient means of meeting global food production requirements that maintaining degraded pastoral and agricultural land. The increase in N_Pmax is modest, considering the level of drylands degradation, and it is possible that N_Pmax could be increased by more than 10%, with a corresponding greater carbon storage.

Considering the IPCC 92d scenario for emissions from fossil fuel combustion, which considers some control measures to reduce the rate of increase in emissions, the average rate of carbon buildup in the atmosphere is around 3.4 Gt C/yr during the next century. The effect of storing carbon through drylands restoration could represent a reduction of up to 15% in total atmospheric carbon buildup. If dryland restoration is justified by a direct environmental benefit, then the benefit of reduced atmospheric carbon comes at no cost. Another perspective is to state that the direct environmental benefit of restoration and the indirect benefit of atmospheric carbon reduction can be combined to justify the costs.

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Literature Cited


