POTENTIAL FOR CARBON SEQUESTRATION IN THE DRYLANDS

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Abstract. Non-forested drylands occupy 43% of the world's land surface yet they are not currently regarded as important in sequestering carbon due to overuse and poor management. Seventy percent of drylands have already undergone moderate to severe desertification and an additional 3.5% drops out of economic production each year. Reversing the trend towards desertification through cultivation of halophytes on saline lands, revegetation of degraded rangelands and other innovative conservation measures could result in net C sequestration in dryland soils of 0.5-1.0 Gt yr^{-1} at a cost of \$10-18 t^{-1} C, based on a 100 yr scenario. Investment in anti-desertification measures in the world's drylands appears to be an economical method to mitigate CO_2 buildup in the atmosphere while accomplishing a major international objective of restoring dryland productivity.

1. Introduction

The previous conference in this series (Wisniewski and Lugo, 1992) advanced the hypothesis that temperate and tropical forests may be sequestering a large portion of the so-called "missing carbon" that is emitted by fossil fuel burning but does not appear in the atmosphere or oceans. Support for this position has come from measured increases in C storage in European forests since the industrial revolution (Kauppi et al., 1992). Logically, if terrestrial ecosystems are already absorbing some of the excess C, those parts of the landscape under direct human management could be managed to store even more C, suggesting a possible mitigation strategy for global warming should it prove necessary.

Unfortunately, most human activities result in C losses from the landscape rather than gains. Land clearing for agriculture is a particular problem. The world's need for

Water, Air, and Soil Pollution **70**: 341–355, 1993.

food increases every year. In 1993, food for 5 x 10^9 inhabitants is required; by the year 2000 food for at least 6 x 10^9 will be needed. Rising standards of living also require greater land areas for food production; the U.S. diet requires approximately 3 times as much land to produce as a typical Asian diet due to greater meat and fat consumption in the U.S. (World Resources Institute, 1990). The developed countries have nearly doubled their agricultural output in the past 40 yr, but there is serious doubt whether such production increases can continue. Even accepting that production increases will continue, FAO predicts that 200 x 10^6 ha of new farmland will be needed in the next century. Forests are presently being cleared for agriculture at an estimated rate of 17 x 10^6 ha yr^{-1} with serious implications for the biospheric C balance (Houghton, 1990). While attention has focused on the forests, parallel land use changes have taken place in the drylands.

2. Drylands and Desertification

The distribution of drylands is governed by the global circulation of the atmosphere. A high-pressure zone of sinking dry air around 30° latitude in each hemisphere is warmed by compression. The warm dry air provides cloudless skies and exposes the land to the full effect of the sun. Brief seasonal invasions of moist air produce little rain, which is erratic in both area and time. The result is two series of deserts surrounded by drylands: in the northern hemisphere lie the Saharan, North American (Colorado, Gila, Mexican), Arabian, Thar and Gobi deserts: to the south are the Patagonian, Kalahari and Australian deserts; all merge gradually into the habitable drylands which border them (Figure 1).

Excluding the hyperarid regions which are largely uninhabited deserts, the drylands total 5.2 x 10^9 ha (Table 1). These are areas where there could be some chance of enhancing productivity either through the use of saline water or better utilization of rainfall. This is a very large land base, exceeding the area of cropland (1.4 x 10^9 ha) or closed forest (4.4 x 10^9 ha) in the world (World Resources Institute, 1990). In fact, drylands occupy some 43% of the total world land area. Most of the drylands are already under management. A significant portion (62%) of the world's irrigated lands are in the drylands. The remainder are used for dryland farming (458 x 10^6 ha) or rangelands (4.5 x 10^9 ha).

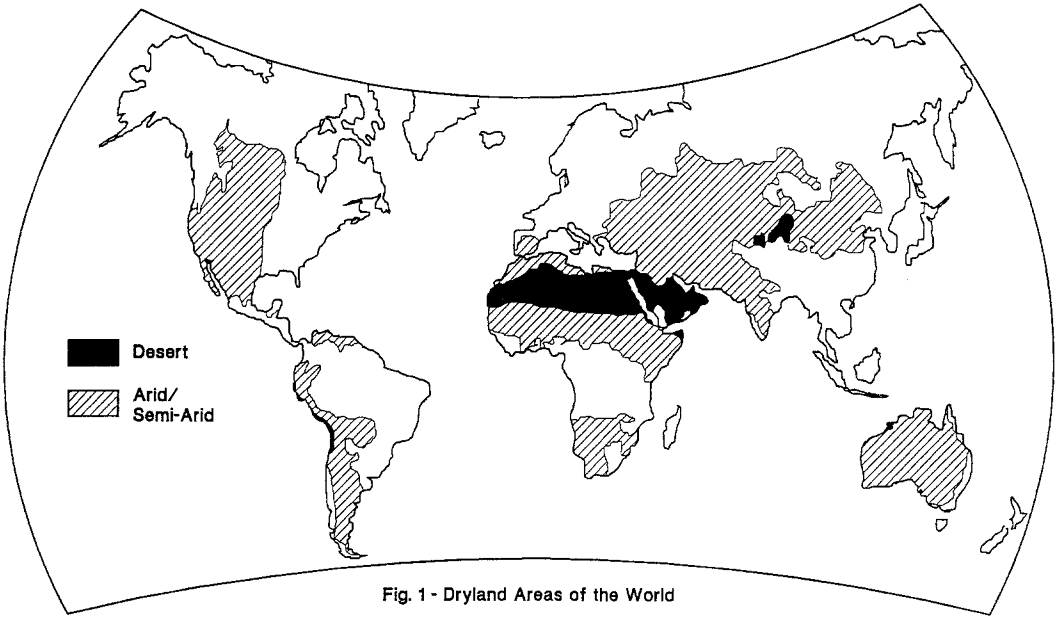

Fig. 1 - Dryland Areas of the World

Table 1. World Drylands (Excluding Hyper-Arid Lands) in Millions of Hectares (Dregne et al., 1991).

	Arid	Semi-Arid	Dry Sub-Humid	Total
Africa	504	514	269	1287
Asia	626	693	353	1672
Australia	303	309	51	663
Europe	11	105	184	300
North America	82	419	232	733
South America	45	265	207	517
World Total	1571	2305	1296	5172

Salt-affected lands form a large subset within the drylands. Coastal deserts and inland salinized soils total 294 x 10^6 and 424 x 10^6 ha, respectively (Glenn et al., 1991a). Most of these are in the hyperarid deserts and do not overlap the areas in Table 1 (see map in Glenn et al., 1991a). Secondary salinization affects irrigated soils. About 43 x 10^6 ha of irrigated lands (or 30% of their total area in the world's drylands) are affected by waterlogging, salinization and alkalinization.

Population increases over the past 30 yr have been rapid in these regions (Table 2), and by 1984 70% of the drylands had undergone moderate to severe desertification due to overuse, resulting in lost primary productivity and CO_2 releases into the atmosphere (Dregne et al., 1991). Current estimates of the amount of drylands lost to economic use due to desertification range from 0.1-10% yr^{-1}, with the highest degradation rates occuring in the driest regions. A weighted mean rate of land lost to desertification is 3.5% yr^{-1} of global drylands (Dregne et al., 1991). It is estimated that annual losses of irrigated land due to abandonment amounts to 1.5 million ha.

Table 2. The Population Increase in the Arid Regions (Eyre, 1985).

	Population (millions)		% Increase	
	1960	1985	1960-1985	Annual
Asia	151.0	270.5	79	3.2
Africa	49.5	96.5	95	3.8
N. Amer.	15.5	26.0	68	2.7
S. Amer.	10.0	17.5	75	3.0
Australia	0.5	0.5	0	0

The UNEP has concluded that whereas at present the drylands contribute little to the global carbon sink, they offer vast areas of land for reforestation, afforestation and other projects to increase carbon storage on the land (Dregne et al., 1991; UNEP, 1991; Kassas et al., 1991).

We will attempt to estimate the potential of these lands for carbon storage and compare the costs with other management options for carbon sequestration. First we will examine the special case for storing carbon in salinized soil using intensive cultivation of halophyte crops then we will consider the case for carbon storage through extensive improvements in management of drylands.

3. Intensive Cultivation of Halophytes

Halophytes are salt-tolerant, native plants which have long been used for grazing; recent developments have shown their value as potential forage (Malcolm, 1986), feed (Glenn et al., 1992a) and oilseed (Glenn et al., 1991b) crops under brackish or even seawater irrigation. The land base for irrigated halophyte production is coastal and inland salt deserts where natural saline water sources are available and in irrigation districts where brackish drain water is available for irrigation of salinized soils. We previously (Glenn et al., 1991a, 1992b) identified 55 desert regions containing an estimated 130 x 10^6 ha of usable land for halophyte plantations. This estimate was approximately 15% of the saline land base and included only flat land that appeared feasible for irrigation from an identified saline water supply.

How much C can be stored on that land depends first upon rates of primary production. We investigated a worst-case scenario for saline water irrigation - the direct use of seawater in a coastal desert environment in the Sonoran Desert (Glenn & O'Leary, 1985; Glenn et al., 1991b). The Electric Power Research Institute and the Salt River Project have funded field trials to measure primary production of halophytes for C storage. Annual dry biomass yields of the best candidate species have ranged from 17-35 t ha^{-1} for a net carbon uptake of 4-8 t ha^{-1} yr^{-1} (Table 3). These yields equal or exceed conventional biomass or forestry yields (e.g. Sedjo, 1989). Projected over the estimated usable world area, intensive halophyte production could absorb approximately 0.6-1.2 Gt C yr^{-1} globally.

Whether significant C sequestration can be achieved depends also upon how much of the primary production enters long-term storage or can be used as replacement for fossil fuels. The particular storage strategy we have investigated is incorporation of biomass into soil for long-term storage in the humic fraction. Dryland soils are typically low in organic carbon, often less than 0.5%. Such soils could conceivably hold greater carbon; in fact, loss of soil organic matter is one of the characteristics of desertification, and most dryland soils do not contain the amount of carbon they could conceivably store under restored conditions (UNEP, 1991). Further, residence time of C in dryland soils can be much longer than forest soils (Gifford et al., 1992). We have conducted experiments in which two types of halophyte biomass and wheat straw were incorporated into irrigated or dry desert soils. Decomposition rates and leaching losses depend upon the salinity of the irrigation supply, the type of biomass and the depth of burial (Olsen, Frye and Glenn, in preparation). Figure 2 shows that decomposition rates of halophyte biomass are significantly slowed on seawater irrigation compared to rates on fresh water.

Table 3. Annual Biomass and Carbon Yields of Seawater-Irrigated Halophytes at Puerto Penasco, 1990-1992. Sample size (n) refers to number of individual plots of a species except for *Sesuvium*, where individual plants within a single plot were sampled. Carbon content was assumed to be 36% of ash-free dry matter.

	n	Annual Yield (t^{-1} ha^{-1}) Biomass		Carbon
		mean	SE	mean
Batis maritima	8	33.95	(.99)	8.2
Atriplex linearis	5	24.27	(1.23)	6.7
Salicornia bigelovii				
Year One	22	22.40	(.70)	5.6
Year Two	9	17.72	(1.32)	4.3
Suaeda esteroa	9	17.22	(1.12)	4.3
Sesuvium portulacastrum	9	16.70	(2.00)	4.2

Using yield data in Table 3 as a production function and the different decomposition experiments as decay functions, we are attempting to predict C storage rates in halophyte farms over time. The decomposition experiments indicate that 30-50% of C might enter long-term storage, but further monitoring of soil C levels will be needed to model the decay function accurately. Nevertheless, all the experiments show that organic matter accumulates over time in halophyte fields where the residues are turned under. The experiments support the hypothesis that even under irrigation, initially C-poor soils typical of the drylands have the capacity for enhanced carbon storage but the magnitude and duration of the storage are still unresolved.

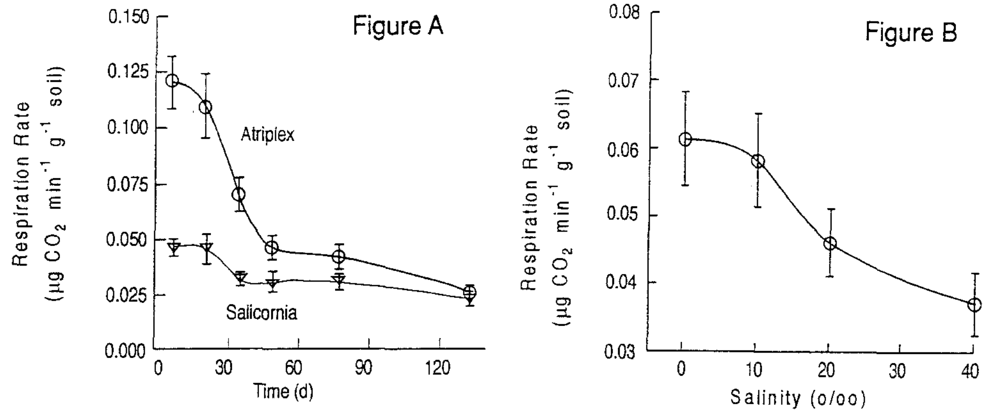

Figure 2. Respiration rate of desert soil amended with 5% w/w <u>Atriplex</u> or <u>Salicornia</u> dry biomass and irrigated with water of 1, 10, 20 or 40 ppt seawater (Olsen, Frye and Glenn, in preparation). Graph A shows differences between biomass types over time across salinities; B shows differences by salinity across biomass types over the whole experiment. Error bars are standard error of estimate.

Water usage and production costs have also been concerns, because early trials utilized much higher quantities of water than could reasonably be used in large-scale practice (Glenn and O'Leary, 1985). However, lysimeter trials with 6 halophyte species have shown that consumptive water use by halophytes is equivalent to conventional crop plants and does not increase with increased salinity of the irrigation supply (Miyamoto et al., in preparation; Glenn et al., in preparation). Even with very salty water (i.e. seawater), high-frequency irrigation with a 0.5 leaching fraction allows high yields with water usage rates within the range of irrigated biomass crops in a similar climate. We have estimated that halophyte biomass can be produced for $44-53 per t compared to $30-45 for conventional biomass crops, and that carbon usage to produce the crop would be 22.5-30.0% of the harvested carbon, assuming all energy inputs were supplied by diesel fuel (Glenn et al., 1992b).

As with tree plantations, the costs of sequestering carbon are high if a halophyte plantation is established solely for the purpose of storing carbon. However, it is more likely that halophytes will be grown as food and animal feed crops with the residues used for carbon storage. In the case of halophyte oilseeds (Glenn et al., 1991b) the straw (containing 90% of total C) is available for carbon sequestration as a by-product; in the case of halophytes grown for forage, the woody stem biomass and roots (ca. 75% of total C) will be available as a by-product. The marginal costs of storing carbon are the costs of plowing under the unused residues - approximately $20 ha^{-1} using typical (Arizona) farm costs, or $4 t^{-1} C for a 5 t ha^{-1} yield. If one-third of buried C enters long-term storage, the cost is $12 t^{-1} C. These costs do not reflect payments to the farmers, however.

The feasibility of halophyte cultivation on a large scale is now under test in the coastal desert near Jubail, Saudi Arabia, where a 320 hectare, seawater farm is growing the oilseed halophyte, Salicornia bigelovii, to supply edible oil and meal for animal feed.

Another role for halophytes is in arresting desertification in drylands. An expert consultation, involving scientists from over 20 countries, met in Nairobi in November 1992 to develop guidelines for returning degraded salt-affected land to productive use via halophytic forage species. The technology (both hardware and software) dealt with in these guidelines is highly relevant to UNEP's plan of action to combat desertification. The guidelines include specific strategies for using extensive (non-irrigated) halophyte plantings to sequester carbon. In these cases, carbon storage is mainly via root biomass, litter accumulation and the standing crop rather than through deliberate harvesting and burial of biomass. They also provide guidelines for planting halophytes in salinized areas of irrigation districts for intensive production.

The largest areas of degraded irrigated lands are situated in the drylands of Asia, followed by North America, Europe, Africa, South America and Australia in descending order. UNEP (1991) estimates that US $250 ha^{-1} (1990 prices) is the average yearly income foregone due to degradation of irrigated land. Dregne et al. (1991) estimates that it would cost between US $500 and $5000 ha^{-1} to restore degraded irrigated land for conventional crops. If we add this to the income foregone (US $250) there is considerable scope to pay for the cost of establishing halophyte plantations (estimated by Le Houerou 1992 to be US $ 500-1000 ha^{-1}).

4. Extensive Biomass Production through Management of Dryland Pastures and Crops

As mentioned, desertification is a severe problem throughout the drylands. UNEP (1991) concluded that 30 years of past anti-desertification programs failed due in large part to insufficient funding. They estimate (Kassas et al., 1991) that \$171-363 x 10^9 will be needed to fund a 20 yr program to arrest the process of land degradation and to restore the already-degraded areas of drylands (Table 4). The program includes afforestation, reforestation, planting of shrubs and grasses, control of grazing lands, planting halophytes on salinized land and numerous other remediation methods.

As desertification proceeds, costs rise dramatically as land passes into higher degradation categories which require greater expense per unit of land. UNEP (1991) estimates the average annual income foregone due to degraded rangelands to be \$23 billion per year. They calculate the cost:benefit of restoring the rangelands as 1:3.5 on a global basis. The funds required for restoration are available internally in 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.

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

Type of Action Needed	Croplands Irrigated	Croplands Rainfed	Rangelands
Preventative Measures	**10-31**	**12-36**	**6-18**
Corrective Measures	**17-50**	**18-55**	**13-38**
Rehabilitation Measures	**21-41**	**22-59**	**80-120**
Totals:	**48-12**	**252-150**	**99-176**

In theory, if an economic incentive were offered in the form of a subsidy for each ton of carbon sequestered on such land, dryland farmers and pastoralists could change their management practices to store carbon. For example, marginal desert rangeland could be allowed to return to perennial shrubs and grasses by restricting clearing and grazing. Stubble could be plowed under where at least a portion would enter long-term storage in the humic fraction. Such speculations are difficult to quantify. However, if a net sequestration rate of only 100 kg C ha^{-1} yr^{-1} could be achieved on the drylands, a total sequestration of 0.5 Gt yr^{-1} would be achieved on a global basis. This would be a significant contribution to removing excess carbon from the atmosphere. Several lines of evidence, reviewed briefly below, suggest that the target figure is acheivable.

The rainfall use efficiency (RUE) calculated for perennial shrub drylands is about 2.5-4.0 kg ha^{-1} mm^{-1} annual rainfall (Le Houerou, 1984). UNEP (cited in Dregne et al.,1991) estimates that 37% of drylands are classified as semi-arid with rainfall in the range of 250-400 mm and a further 17% is classified as subhumid (rainfall 400-550 mm). Applying the RUE factors we calculate on a global basis that semi-arid regions have the potential to produce 2.76 Gt yr^{-1} of above ground biomass and the subhumid regions 2.33 Gt yr^{-1} (total C = 2 Gt yr^{-1}).

The biomass figures quoted above are for above ground biomass. Root biomass, so critical in the equation, is likely to be at least as high or even higher (Kozlowski, 1972). Furthermore, C sequestered in roots of dryland plants is likely to remain locked away for a long time because of slower decomposition rates belowground. Sims and Singh (1971) found that about 85% of the total standing crop of photosynthesizing plants in North American drylands was belowground. Gifford et al. (1992) estimated that 30% of total primary productivity entered long-term soil storage in Australian soils. Hence, dryland soils could theoretically become net sinks for 0.6 Gt yr^{-1} C, based on RUE production rates and soil storage estimates, whereas at present they are probably net sources (Dregne et al., 1991).

Can the theoretical RUE be approached by revegetating degraded drylands? Le Houerou (1992) evaluated standing crops and productivities of Mediterranean arid zones that were revegetated with Atriplex spp. In a 100-400 mm yr^{-1} rainfall area, plant stands were as high as 20 t ha^{-1} with annual productivity rates of 3-5 t ha^{-1}. He estimated that standing crops and productivity rates at least half these values could be realistically acheived over the area of 550 million ha that had been subjected to desertification. Hence, the theoretical RUE were actually exceeded under semi-managed conditions.

Rainfed croplands offer a further opportunity to sequester carbon through burial of the stubble. Worldwide, rainfed croplands occupy about 1.3×10^9 ha although an estimated $7-8 \times 10^6$ ha are lost each year. Improved stubble (crop residue) handling practices could lead to major savings in C sequestering. For example, a 2 t crop of wheat grain leaves about 4 t of stubble. Many regions have yields of grain in excess of 3 t ha^{-1} with concomitant yields of residues. Globally, 1.8 Gt of grain are produced in the drylands, with a yield of stubble of at least 7.5 Gt (containing 2.7 Gt C). If the stubble were plowed under and even 5% entered long term storage in the soil, 0.14 gt C yr^{-1} would be sequestered by this practice alone.

5. Potential for increased production as function of rainfall

It is predicted that the greenhouse effect will cause changes in the distribution of rainfall. Climatic changes will be uneven and some dryland areas will receive less rather than more rainfall but globally the drylands are expected to become more moist (Henderson-Sellars & Blony, 1989). In some cases this will stimulate greater potential productivity over large areas of marginal land (Squires & Tow, 1991). For example, yield increases up to 10-15 per cent might be expected for wheat, rice, and barley and increases from 0-10 per cent for corn, sorghum and sugar cane. Any augmentation of rainfall as a result of climatic change could influence biomass production. Rangeland vegetation responds positively to any increase in precipitation. It has been reported (NRC, 1975) that a direct ratio of increase in herbage biomass to increase in supplementary water occurs in dry areas: yield is increased about 6,700 kg/ha of forage per 2.5 cm of annual precipitation in semidesert, and about 10,700 kg/ha in midgrass areas. If the potential productivity increases are to be realized, however, the lands that have been lost to desertification will have to be managed or restored.

6. Conclusions

Restoring productivity in the drylands will have a beneficial effect on at least short term carbon uptake in these lands (over a period of approximately 20 years). If the pasture drylands were restored to natural rates of productivity based on rainfall, they would absorb some 2-3 Gt C yr^{-1}. Much of this would be stored in the standing crop of trees and shrubs regrowing on the landscape. Additional carbon amounting to 0.6-1.2 Gt yr^{-1} could be absorbed through intensive halophyte plantations, and plowing under of cereal stubble could store 0.1-0.2 Gt C yr^{-1}. The annual enhanced production of approximately 3 Gt C yr^{-1} would lead to long-term carbon storage in the soil although at reduced efficiency. The pertinent question is: would investment in dryland programs be cost effective in terms of C storage compared to other potential offsets?

During this workshop but independent of our analyses in this paper, the CENTURY model was used to estimate rates of C storage in non-agricultural dryland soils over a 100 yr period, using two management scenarios (Ojima, 1993). In the first scenario, a 80% biomass removal rate was used, to simulate present overuse of drylands; in the second scenario, a 30% removal rate was used, to simulate optimum management practices. The results indicated that under good management and given likely increases in primary production due to climate change in these regions, pasture dryland soils could become a net C sink of 0.5 Gt yr^{-1}, whereas under present management they will continue to represent a net source of C, due to releases from the soil not compensated by inputs on overgrazed or eroded lands.

If anti-desertification programs to restore rangelands were funded at levels recommended by UNEP (1991) and resulted in 0.5 Gt yr^{-1} of C sequestration as predicted, the costs would be \$10-18 t^{-1} C. This is a reasonable cost compared to reforestation, tree plantations and other C offsets (Kinsman and Trexler, 1993). A similar amount of C could theoretically be sequestered at similar cost using halophyte crop residues on saline lands. Cereal stubble could contribute an additional 0.1-0.2 Gt of C storage. Total C sequestration could well exceed 1 Gt yr^{-1}. We conclude that C sequestration in dryland soils is feasible and cost effective.

Creating an economic linkage between fossil fuel burning and restoration of drylands to store C would appear to be a worthwhile goal in view of the importance of the drylands in global food production. Since the effects of CO_2 enrichment on climate are uncertain, those actions that make sense even in the absence of global warming have been recommended as present action steps (the "no regrets" policy). Restoration of productivity to the drylands through halophyte crops, rehabilitation of rangelands and other management practices falls into this category of action step.

Acknowledgements

This work is supported by the Electric Power Research Institute and the Salt River Project under RP8011-3. We thank Al Qöyawayma, Jan Miller, Lou Pitelka and Sy Alpert for support and encouragement throughout the study.

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