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CARBON SEQUESTRATION IN DRYLAND ECOSYSTEMS OF WEST ASIA AND NORTH AFRICA

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ABSTRACT

The West Asia–North Africa (WANA) region has a land area of 1·7 billion ha, and a population of 600 million. Desertification and soil degradation are severe problems in the region. The problem of drought stress is exacerbated by low and erratic rainfall and soils of limited available water holding capacity and a soil organic carbon (SOC) content of less than 0·5 per cent. The SOC pool of most soils has been depleted by soil degradation and widespread use of subsistence and exploitative farming systems. The historic loss of a SOC pool for the soils of the WANA region may be 6–12 Pg compared with the global loss of 66–90 Pg. Assuming that 60 per cent of the historic loss can be resequestered, the total soil-C sink capacity of the WANA region may be 3–7 Pg. This potential may be realized through adoption of measures to control desertification, restore degraded soils and ecosystems, and improve soil and crop management techniques that can enhance the SOC pool and improve soil quality. The strategies of soil C sequestration include integrated nutrient management (INM) and recycling, controlled grazing, and growing improved fodder species on rangeland. Improved technologies for cropland include use of INM and biofertilizers, appropriate tillage methods and residue management techniques, crop rotations and cover crops, and water and nutrient recycling technologies. Through adoption of such measures, the potential of soil-C sequestration in the WANA region is 0·2–0·4 Pg C yr^{-1}. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: Middle East; West Asia; North Africa; desertification; greenhouse effect; intensive agriculture

INTRODUCTION

The WANA Region

The West Asia–North Africa (WANA) region extends from Pakistan in the east to Morocco in the west, and from Turkey in the north to Ethiopia and Sudan in the south. The region is mainly characterized by the Mediterranean climate, with cool to cold wet winters and warm to hot dry summers (Kassam, 1981). Countries surrounding the Mediterranean Sea are characterized by a milder climate due to maritime effect and low elevation. Rainfall is low, highly variable, and ranges from 100–600 mm yr^{-1} (Dennett, 1987). Winter rains normally occur from October–February (Harris, 1995), and the pattern is different in southern Asia (e.g., Iran, Afghanistan, Pakistan) where monsoon rains occur in summer (July–September). Drought stress, a severe problem in rainfed agriculture, is exacerbated by erratic and unreliable rains.

Predominant soils of the WANA region are derived from limestone residuum, and hence are calcareous (FAO, 1978, 1979; Kassam, 1981, 1988). These soils include Inceptisols, Lithosols or shallow soils, Entisols, Aridisols, and others comprising sand dunes and desert pavements (Dregne, 1976; Kassam, 1981; FAO-UNESCO, 1974). Distribution of cropland soils (with growing period of 75–210 days) of the region is shown in Table I. Soils exhibit a strong variability even over short distances (Shroyer *et al.*, 1990), and there is a close relationship between

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Table I. Distribution of major soil groups in North Africa and West Asia with a 75 to 210-day growing period

Soil group	North Africa (Mha)	West Asia (Mha)
Cambisols	7·0	10·2
Lithosols	5·4	20·6
Luvisols	3·8	7·7
Fluvisols	2·1	1·9
Regosols	2·4	7·9
Vertisols	1·2	4·1
Xerosols	5·6	22·0
Yermosols	3·1	6·3
Others	4·1	9·1
Total	34·7	89·8

Source: adapted from Kassam, 1981; Matar *et al.*, 1992.

rainfall and soil organic matter content (Ryan *et al.*, 1997). Most soils of dryland ecosystems are characterized by low soil organic carbon (SOC) content, but contain relatively large content of soil inorganic carbon (SIC) or carbonates (Lal *et al.*, 2000). The SOC content of most soils is 0·1–0·5 per cent, and rarely exceeds 1·0 per cent (Ryan and Monem, 1998; Matar *et al.*, 1992).

Land Use and Farming Systems

The total land area of the region is 1·6 billion hectares (Bha) comprising 140 million hectares (Mha) of arable land and 13 Mha of permanent crops (Table II). The mean per capita arable land area of the region is 0·23 ha, with a range of 0·04 ha for Egypt to 0·59 ha for Sudan. However, the population of the region is rapidly increasing

Table II. Land use in some countries of the Mediterranean region

Country	Area (Mha)	Arable land (Mha)	Permanent crops (Mha)	Population in 1998 (millions)	Per capita arable land (ha)
Afghanistan	65·2	7·9	0·1	21·4	0·37
Algeria	238·2	7·5	0·5	30·0	0·25
Egypt	100·1	2·8	0·5	66·0	0·04
Eritrea	11·8	0·4	0·002	3·6	0·11
Ethiopia	110·4	9·9	0·7	59·6	0·17
Iran	162·2	17·8	1·7	65·8	0·27
Iraq	43·8	5·2	0·3	21·8	0·24
Jordan	8·9	0·3	0·1	4·7	0·06
Kuwait	1·8	0·006	0·001	1·8	0·003
Lebanon	1·0	0·2	0·1	3·2	0·06
Libya	176·0	1·8	0·3	5·3	0·34
Morocco	44·6	8·7	0·8	27·4	0·32
Oman	21·2	0·02	0·05	2·4	0·008
Pakistan	79·6	21·0	0·6	148·2	0·14
Saudi Arabia	215·0	3·7	0·1	20·2	0·18
Sudan	250·6	16·7	0·2	28·3	0·59
Syria	18·5	4·8	0·8	15·3	0·31
Tunisia	16·4	2·9	2·0	9·3	0·31
Turkey	77·5	26·6	2·6	64·5	0·41
UAE	8·4	0·04	0·04	2·3	0·018
Yemen	52·8	1·6	1·4	16·9	0·09
Total	1704·0	139·8	12·8	618.00	0·20

Source: adapted from FAO, 1998a.

Table III. Percent increase in population of some countries (millions)

Country	Year							
	1900*	1925*	1950*	1975*	1980*	1998†	2000‡	2025‡
Algeria	5	6	9	16	19	30	32	47
Egypt	10	14	20	37	42	66	68	96
Morocco	5	6	10	18	20	27	28	39
Pakistan	16	22	33	70	82	148	156	263
Sudan	6	7	9	13	19	28	29	46

*McEvedy and Jones, 1978.
†FAO, 1998a.
‡Engelman, 2000.

(Table III), causing a rapid decrease in the per capita land area, further jeopardizing the natural resources that are already under great stress.

The statistics on land use for the region in 1990 are shown in Table IV. Out of a total land area of 1·6 Bha, predominant land use includes 34·4 Mha irrigated cropland, 74·2 Mha rainfed cropland, 828·3 Mha rangeland, and 665·3 Mha hyperarid land. However, the irrigated land area has increased during the 1990s, and was estimated at 47·1 Mha for 1997–98 (Table V). With a total cropland area of 108·6 Mha and fertilizer use of 8·6 Mt (metric ton = 1000 kg), the average rate of fertilizer use on cropland is 80 kg ha^{-1}

The cropping period is normally from October–November (at the onset of fall rains) to May–June when harvesting occurs. As the soil has little or no residual moisture after a long dry season, adequate rainfall is crucial for successful crop production. In regions with winter rainfall, rainfed cropping is dominated by cereals (e.g., wheat, barley) and legumes (e.g., chickpea, faba bean, peas, and forage legumes), combined with livestock production.

Table IV. Land use in different agroecoregions

Country	Irrigated cropland	Rainfed cropland	Rangeland	Hyperarid	Total drylands
			1000 ha		
Afghanistan	2660	2734	50 928	0	56 322
Algeria	338	6934	38 120	190 063	235 455
Egypt	2486	10	2604	94 900	100 000
Ethiopia	94	10 956	69 556	1400	82 006
Iran	5287	2849	142 024	2802	152 962
Iraq	1750	1950	38 395	0	42 095
Jordan	43	375	6862	1820	9100
Kuwait	1	0	2306	0	2307
Lebanon	86	214	688	0	988
Libya	234	1659	17 172	157 655	176 720
Morocco	525	7484	36 693	1050	45 752
Oman	41	6	19 642	7506	27 195
Pakistan	15 440	4807	60 000	0	80 247
Saudi Arabia	415	760	112 345	126 480	240 000
Sudan	1700	5108	142 542	68 700	218 050
Syria	652	4971	12 945	0	18 568
Tunisia	215	4258	7968	3037	15 478
Turkey	2150	16 893	33 914	0	52 957
UAE	5	0	1008	8197	9210
Yemen	309	1209	32 590	1692	35 800
Total	34 431	73 177	828 302	665 302	1 601 212

Source: modified from Dregne, 1992.

Table V. Irrigation in the WANA region

Country	Irrigated area (1000 ha)	Fertilizer use (1000 Mt)
Afghanistan	2800	5
Algeria	560	97
Egypt	3300	1010
Eritrea	28	6
Ethiopia	190	132
Iran	7265	1152
Iraq	3525	340
Jordan	75	23
Kuwait	5	1
Lebanon	117	60
Libya	470	62
Morocco	1251	304
Oman	62	7
Pakistan	17 580	2659
Saudi Arabia	1620	327
Sudan	1950	77
Syria	1168	368
Tunisia	380	96
Turkey	4200	1826
UAE	72	31
Yemen	485	19
Total	47 103	8602

Source: FAO, 1998 a and b.

Principal livestocks are sheep and goats. In general, crop yield increases with increase in rainfall amount (Ryan *et al.*, 1991). In regions with high rainfall ($>350\,mm\,yr^{-1}$), wheat is grown in rotation with beans, and barley replaces wheat in the drier regions with a limited range of alternate crops. Barley is used mainly as feed in systems where livestock forms a major output. In both wheat-based and barley-based systems, fallows may be weed-free or the traditional weedy fallows for winter followed by spring grazing (Cooper *et al.*, 1987; Tully, 1989; Harris, 1995).

Soil Degradation and Desertification

Both vegetation and soil resources are prone to severe degradation in the Mediterranean region (Brandt and Thornes, 1996; Conacher and Sala, 1998), and in other dryland ecosystems of the world (Kishk, 1986; UNEP, 1991; Dregne, 1992). The WANA region is characterized by a severe problem of soil degradation by salinization, accelerated erosion, nutrient imbalance, depletion of SOC, and the overall desertification. Land area affected by desertification in the WANA region is estimated at 11·3 Mha of irrigated cropland, 50·0 Mha of rainfed cropland, and 709·2 Mha of rangeland. A total of 770·2 Mha or 45·2 per cent of the total land area is subject to some degree of desertification (Table VI). On the basis of land area affected, desertification is a severe problem in Iran, Sudan, Saudi Arabia, Ethiopia, Pakistan, Afghanistan, Turkey, Algeria and Morocco (Table VI). In addition, irrigated land is prone to salinization. The total area affected by salinization is estimated at 89·1 Mha (Table VII). Secondary salinization of irrigated land is a severe problem in Egypt, Iran, Iraq, Pakistan and Syria. Soil degradative processes adversely affect biomass productivity, reduce the amount of biomass returned to the soil, and deplete the SOC pool.

SOIL CARBON POOL AND THE GREENHOUSE EFFECT

Global Soil Carbon Pool and the Greenhouse Effect

The global soil-C pool, comprising SOC and SIC components, is about 4·1 × the biotic pool and about 3·0 × the atmospheric-C pool (Batjes, 1996, 1998; Nordt *et al.*, 2000; Lal, 2001a). The SOC pool includes highly active

Table VI. Estimates of the land area affected by desertification

Country	Irrigated cropland	Rainfed cropland	Rangeland	Total	% of the total area*
			1000 ha		
Afghanistan	655	1480	45 900	48 035	73·6
Algeria	50	6450	34 300	40 800	17·2
Egypt	751	1	2100	2852	2·8
Ethiopia	6	6800	59 000	65 806	53·8
Iran	1200	2000	128 000	131 200	80·9
Iraq	1250	1400	34 500	37 150	84·9
Jordan	13	210	6200	6423	71·2
Kuwait	0	0	1960	1960	90·0
Lebanon	6	130	620	756	75·6
Libya	55	580	13 700	14 335	8·2
Morocco	51	5200	33 000	38 251	85·9
Oman	11	3	17 700	17 714	83·5
Pakistan	6100	3360	54 000	63 460	79·8
Saudi Arabia	260	460	90 000	90 720	42·2
Sudan	360	2090	114 000	116 090	46·3
Syria	110	3500	11 600	15 210	82·2
Tunisia	7	2940	6800	9810	59·8
Turkey	290	12 700	28 900	41 890	54·1
UAE	2	—	900	902	10·7
Yemen	50	780	26 000	26 830	50·7
Total	11 277	50 084	709 180	770 491	45·2

Source: modified from Dregne, 1992.
*Based on the total area shown in Table I.

Table VII. Distribution of salt-affected soils in the WANA region

Country	Area of salt-affected soil (1000 ha)	% of irrigated land affected by salinization
Afghanistan	3101	NA
Algeria	3150	10–15
Egypt	7360	30–40
Eritrea	—	NA
Ethiopia	11 033	NA
Iran	27 085	30
Iraq	6726	50
Jordan	180	16
Kuwait	209	NA
Lebanon	—	NA
Libya	2457	NA
Morocco	1148	NA
Oman	290	NA
Pakistan	10 456	40
Saudi Arabia	6002	NA
Sudan	4874	20
Syria	532	30–50
Tunisia	990	NA
Turkey*	2403	NA
UAE	1089	NA
Yemen	NA	NA
Total	89 085	

Source: adapted from Goudie, 1990; Balba, 1995; Cangir *et al.*, 2000.
*3·1% of the total land area.

humus and relatively inert charcoal carbon. The 'humus' is the principal ingredient of the SOC. The latter includes a mixture of plant and animal residue at various stages of decomposition, of substances synthesized microbiologically and/or chemically from the breakdown products, and of the bodies of live microorganisms and small animals and their decomposing products (Schnitzer, 1991). The SIC is an important constituent in subsurface horizons of soils in arid and semiarid regions, and comprises primary and secondary carbonates. The atmospheric C pool is increasing, mostly at the expense of the geologic, soil and biotic C pools. Depletion of the soil C pool is accentuated by soil degradation and desertification, and that of the biotic pool by deforestation, conversion of natural to agricultural ecosystems and biomass burning. There is a close link between the soil quality and the soil C pool, and the depletion of the latter leads to soil degradation and vice versa.

The atmospheric C pool has increased steadily from 280 ppmv in the pre-industrial era to 365 ppmv in 2000, and is increasing at the rate of 1·8 ppmv or 0·5 per cent or 3·3 Pg C yr^{-1} (IPCC, 1995). Enrichment of the atmospheric C pool has been caused by the combustion of fossil fuel, cement manufacturing, land-use change and soil cultivation. Global contribution of fossil fuel combustion to atmospheric enrichment of CO_2 is estimated at 270 ± 55 Pg C (IPCC, 2000). The global historic loss of C from the soil C pool is estimated at 55 Pg by IPCC (1995) and 66–90 Pg by Lal (1999, 2001b). Of the loss from the soil C pool, 19–32 Pg is due to accelerated soil erosion, which on desertified lands currently leads to emission of 0·21–0·26 Pg C yr^{-1} (Lal, 1999).

Carbon Pool in Soils of Dryland Ecosystems

Soils of dryland ecosystems are characterized by low SOC content, and low nutrient reserves especially N. The SOC content is generally low, but is more in soils of wetter than drier regions, and in those containing high rather than low clay contents. Most soils have low SOC content ranging between 0·2 and 0·8 per cent. Low levels of SOC content have also been reported from soils of Pakistan (Rashid *et al.*, 1988), Iraq (Aziz *et al.*, 1988), and elsewhere in the WANA region (Amar and Houssa, 1988; Bowman *et al.*, 1999; ICARDA, 1991; Khalil and El-Shinawi, 1989; Osman *et al.*, 1999; Ryan and Matar, 1988). However, not all soils have low SOC content, which in some soils may be 1·5–2·0 per cent (Yurtsever and Gedikoglu, 1988).

The low biomass productivity of soils of these ecoregions, a principal cause of the low SOC pool, is due to drought stress, desertification and low water- and nutrient-use efficiencies. The soil C pool to 1 m depth is about 300 Pg for the hot desert ecosystems, and 135 Pg for the semiarid tropics. Estimates of the soil C pool of the WANA regions are not available.

The SOC content is generally high in soils of the undisturbed ecosystems, and cultivation and cropping leads to depletion of the SOC pool. Both rate and the magnitude of the historic depletion of the SOC pool are more in soils managed by subsistence methods of farming, based on low or no external input and low yields (Lal, 2001a).

TECHNOLOGICAL OPTIONS FOR SOIL CARBON SEQUESTRATION

Historic Loss of Soil Carbon Pool

The largest potential of soil-C sequestration lies in restoration of degraded soils and ecosystems. These soils, especially those affected by accelerated erosion (by water and wind) and salinization, have lost a large fraction of the original soil-C pool. The magnitude of the loss may be 10–30 Mg C ha^{-1} (1 Mg = megagram = 10^6 g = 1 metric ton) (Lal, 2001b), depending on the antecedent pool and the severity of the degradative process. With total managed land area of 153 Mha, the historic loss of SOC may be 1·5–4·5 Pg. Assuming the loss of SOC from rangeland in the range of 5–10 Mg ha^{-1} (Lal *et al.*, 1999), the historic loss from 828 Mha of rangeland may be 4·1–8·3 Pg. Thus, total loss of soil-C from the WANA region may be 6–12 Pg. These estimates provide a reference point with regard to the sink capacity of the soils. Assuming that 60 per cent of historic loss can be resequestered (Cole, 1996), the potential of soil-C sequestration for the WANA region may be 3–7 Pg C over a 50 year period.

There are several strategies of resequestration of the historic loss of C in soils of the dryland ecosystems. These strategies can be grouped into the three categories in the following sections.

Desertification Control and Restoration of Degraded Soils and Ecosystems

Soils in which the SOC pool has been depleted by degradative processes because of land misuse and soil mismanagement generally exhibit a linear increase in SOC in direct proportion to increased C inputs through adoption of soil restorative measures. Recommended technologies for desertification control and soil restoration include establishing the vegetative cover with appropriate species adapted to the ecosystem, controlled grazing, water harvesting, growing halomorphic plants, and enhancing nutrient recycling mechanisms (Squires *et al.*, 1998; Lal *et al.*, 1999; Lal, 2001b). Adoption of these technologies would reverse degradative trends, enhance soil quality and sequester C in soil and biota.

The potential of soil C sequestration through desertification control and soil restoration is generally in the order of irrigated cropland > rainfed cropland > rangeland. There are numerous traditional techniques of soil and water conservation that are widely used in the North African region. Important among these are dry-stone walls built on the contour. This technique allows the natural construction of small terraces behind the old walls. Stones and large rocks are also used as gabiens to control gully erosion. In addition, there are several modern erosion control practices including vegetative barriers including lines of fruit trees with multipurpose objectives. The effectiveness of these techniques has been a debateable issue (Heusch, 1995). Some of the improved management options for restoration of rangeland/grazing land and cropland are listed in Table VIII. Technological options for grazing land include improving soil P level, replacing native with improved forage species through innovative seed dispersal system, controlled grazing, and integration of crop/livestock systems in regions with favorable rainfall distribution. Improved systems of cropland management include appropriate methods of seedbed preparation, supplemental irrigation and water harvesting, nutrient management, and suitable crop rotations that eliminate fallow (Table VIII). The rate of soil C sequestration, both SOC and SIC, are generally low in dryland ecosystems (Lal, 1999). Adoption of soil-specific restorative measures may lead to SOC sequestration at the rate of 0·1–0·2 $Mg\,ha^{-1}\,yr^{-1}$ for irrigated cropland and 0·05–0·1 $Mg\,ha^{-1}\,yr^{-1}$ for both rainfed cropland and rangeland. The leaching of SIC is an important process in irrigated systems (Nordt *et al.*, 2000), and the rate of leaching of carbonates may be 0·2–0·3 $Mg\,ha^{-1}\,yr^{-1}$ for lands under a canal irrigation system (Lal *et al.*, 1999). In other lands, the rate of formation of secondary carbonates and leaching may be low.

Calculations in Table IX show the potential of soil C sequestration through desertification control and restoration of degraded ecosystems. The total potential is 2·0–5·1 Pg C over a 50 year period at an average rate of 40–100 $Tg\,C\,yr^{-1}$ (1 Tg = teragram = 10^{12} g = 1 million metric tonnes).

In addition to desertification, there are 89 Mha of salt-affected soils in the WANA region. Most of these soils prone to secondary salinization are irrigated lands, and the technology for reclamation of salt-affected soils is well known (Gupta and Abrol, 1990). Some forage species can also be grown on saline-sodic soils for biomass production and soil reclamation (Qadir *et al.*, 1996). Restoration of salt-affected soils can lead to SOC sequestration at the rate of 0·1–0·2 $Mg\,C\,ha^{-1}\,yr^{-1}$ (Garg, 1998). Therefore the potential of SOC sequestration is as shown in Equation 1:

$$\text{SOC sequestration through reclamation of salt-affected soils} = (89\,\text{Mha}) \times (0{\cdot}1 - 0{\cdot}2\,\text{Mg C ha}^{-1}\,\text{yr}^{-1}) = 9 - 18\,\text{Tg C yr}^{-1}. \quad (1)$$

Biofuel Production

Despite large fossil fuel reserves of the WANA region, the potential of biofuel production through establishment of specific biofuel plantations cannot be overemphasized. Afforestation is an important strategy, and several multipurpose trees can be grown in dryland ecosystems. However, many arid and semiarid ecoregions may not support trees. Thus the selection of appropriate site and specific tree species are critical. Afforestation has been widely practiced in Morocco and Algeria. In Morocco, 153 500 ha were reforested in 1939. In the first 20 years of independence, 370 000 ha were forested, but by 1977 only 500 000 ha of forests were planted. At present, 1 Mha of forest have been planted (Conacher and Sala, 1998). In Algeria, 8200 ha were reforested from 1850–1930 (Plit, 1983). During the period 1963–81, 560 000 ha were reforested (Conacher and Sala, 1998). Some of these plantations can be used as sylvopastoral systems and others as permanent meadows.

Table VIII. Some improved management systems for soil organic carbon sequestration and soil quality enhancement

Farming system	Improved management	Country/region	Reference
A. Grazing/rangeland			
1. Soil P level	Residual phosphate and grassland restoration	Syria, WANA	Osman *et al.*, 1999; Matar *et al.*, 1992
2. Controlled grazing	Extending growing period of shrubs	Egypt	Duivenbooden, 1993
3. Seed dispersal	Using sheep to disperse leguminous seeds	Syria	Ghassali *et al.*, 1998
4. Fodder trees	Nutrient cycling		Le Houreou, 2000
5. Crop/livestock integration	Improving carrying capacity	WANA	Thomson and Bahhady, 1995
B. Cropland			
1. Tillage methods	Time and method of seedbed preparation	Syria, Dryland	Ryan, 1998; Schomberg and Jones, 1999
2. Supplemental irrigation	Increasing wheat yield	Syria	Oweis *et al.*, 1998
3. N fertilization	50–100 kg N ha^{-1}	Syria	Oweis *et al.*, 1998
4. N and P management	Enhancing biomass yield	Sudan, WANA	Farah (paper presented at 2nd Afr. Soil Sci. Soc. Conf. Cairo, 1993); Matar *et al.*, 1992
5. Water/nutrient recycling	Sewage irrigation	Egypt	El-Naim *et al.*, 1987
6. Crop rotations	Legume-based systems	Syria, Midemanian region	Jenkinson *et al.*, 1999 Osman *et al.*, 1990

Table IX. Potential of soil C sequestration through desertification control and restoration of degraded soils in the WANA region

Ecosystem	Land area (Mha)	Rate of soil C sequestration with improved management (Mg C ha^{-1} yr^{-1})			Total potential over 50 yrs (Tg C)
		SOC	SIC	Total	
Irrigated cropland	11·3	0·1–0·2	0·2–0·3	0·3–0·5	170–283
Rainfed cropland	50·1	0·05–0·1	0·01–0·1	0·06–0·2	150–500
Rangeland*	578·3	0·05–0·1	0·01–0·05	0·06–0·15	1735–4337
Total					2055–5120

*The rangeland area has been reduced by 250 Mha allocated for biofuel production.

There is a wide range of tree species that can be grown in the WANA region. Some tree species adapted for these ecosystems include tamarisk (*Tamarix* spp.), gum tree (*Eucalyptus* spp.), lencaena (*Leucaena* spp.), cypress (*Cupressus* spp.), casuarina (*Casuarina* spp.), mesquite (*Prosopis* spp.), neem (*Azadirachta* spp.), acacia (*Acacia* spp.), teak (*Tectona grandis*), casia (*Casia siamea*) and many others (Lal *et al.*, 1999). Further, several tree species are tolerant to high salinity. In addition to biofuel production, tree plantations also enhance SOC content. Ruecker *et al.* (1998) observed in eastern Spain that natural tree establishment on degraded soils significantly increased SOC content in the 0–10 cm layer after 30 years of growth. In northeastern Sudan, Alstad and Vetaas (1994) observed improvement in soil quality under the stand of *Acacia tortillis.* Garg (1998) observed that establishement of mesquite (*Prosopis juliflora.*) plantation on salt-affected soils in northwestern India increased SOC pool from 10 Mg ha^{-1} to 45 Mg ha^{-1} over an eight year period. This increase is over and above that of the above-ground biomass that was useful as fuelwood.

With a coordinated effort, it is assumed that 250 Mha of rangeland (35 per cent of desertified rangeland) can be grown to dedicated species for fuelwood production. Even at a modest rate of biomass production of 0·5–1 Mg ha^{-1} yr^{-1}, the total biomass produced is 0·25–0·5 Pg yr^{-1}. The average biofuel C offset on this land is shown in Equation 2:

$$\text{Average biofuel C offset} = 250\,\text{Mha} \times \,(0{\cdot}5 - 1\,\text{Mg ha yr}^{-1}) \times (0{\cdot}7) = 88 - 175\,\text{Tg C yr}^{-1} \quad (2)$$

The potential of SOC sequestration in 250 Mha of forested lands, at the modest rate of 0·1–0·3 Mg ha^{-1} yr^{-1}, can be as much as 25–75 Tg C yr^{-1}.

Agricultural Intensification on Prime/Undegraded Soils

Total arable land in the WANA region is 108·6 Mha, of which 61·3 Mha is degraded or desertified and have been accounted for in the restoration of degraded soils and desertification control. The remainder 47·5 Mha of cropland and 12·8 Mha of land under permanent crops (a total of 60 Mha) has a potential of soil C sequestration through adoption of improved agricultural practices. The potential of these practices is especially high in regions that receive favorable rainfall and have high irrigation potential. The data in Table X show the areal extent of regions with different rainfall regimes in some countries of the WANA region. Soils of these regions would respond to adoption of technologies leading to agricultural intensification and high yields.

There is a vast potential for improvement of agriculture in the Middle Eastern region (Salman, 1990; Clawson *et al.*, 1991). There are several technological interventions that can enhance biomass yield and lead to soil C sequestration. Use of biosolids and organic material in agricultural soils has been shown to increase SOC content in several soils of Egypt (Abdel-Ghaffar, 1982; El-Abedine and Hosny, 1982; Moustafa, 1982; Makawi, 1982; Riad, 1982) and elsewhere in the WANA region. Soil fertility management, especially judicious use of N and P through INM, is an important option. Although the importance of organic manure in increasing cereal yields is well recognized, it is unlikely that there is a sufficient quantity available on a regional basis. Therefore, adopting the

Table X. Rainfall distribution in dryland ecosystems of the WANA region

Country	Total area (Mha)	Non-arid/non-desert (> 400 mm)	Arid (100–400 mm)	Desert (50–100 mm)	Desert wasteland (< 50 mm)
Egypt	6·0	0·0	0·5	3·5	2·0
Iraq	43·5	4·8	29·1	9·6	0·0
Jordan	9·8	1·5	4·0	2·5	1·8
Kuwait	1·8	0·0	1·8	0·0	0·0
Oman	21·2	0·2	1·2	9·1	10·7
Qatar	2·2	0·0	0·0	2·2	0·0
Saudi Arabia	215·0	1·0	20·0	124·0	70·0
Syria	18·5	1·0	15·7	1·0	0·0
Turkey	78·1	67·1	11·0	0·0	0·0
UAE	8·4	0·0	0·0	8·4	0·0
N. Yemen	19·5	3·0	14·0	2·5	0·0
S. Yemen	33·2	1·0	2·0	23·2	7·0

Source: adapted from a paper presented by H. N. Le Houreou and L. Boulos at IVth Congress International des Terres de Parcours, 1991.

strategy of INM is crucial to sustainable use of soil and water resources. Ryan and Monem (1998) demonstrated improvement in soil quality through soil fertility management for sustained production. Matar *et al.* (1992) showed that judicious application of P to soils of the WANA region improve water-use efficiency, enhance biomass production and improve crop yield. Further, there is a close link between water and nutrient use efficiencies, and in increasing the SOC content (Cooper *et al.*, 1987). For Vertisols in the Ethiopian Highlands, Wakeel and Astartke (1996) suggested adoption of recommended agricultural practices (RAPs) (e.g., fertilizer use, water conservation, new varieties and improved cropping systems) to minimize risks of soil degradation and improve soil quality.

Legume-based crop rotations are important to strengthening nutrient cycling mechanisms (Ryan *et al.*, 1997). In Saudi Arabia, Shahin *et al.* (1998) observed that introducing alfalfa in rotation with wheat grown on a sandy soil decreased salinity and increased SOC content threefold as compared with continuous wheat. In Algeria, Arabi and Roose (1992) and Roose (1996) observed beneficial effects of improved crop rotations and sylvopastoral systems on soil and water conservation and enhancement of soil quality. In Syria, Ryan (1998) reported a significant increase in SOC content by elimination of fallow and application of recommended rates of fertilizers. When Medicago was grown in a long-term rotation, increase in SOC content was observed to 1 m depth, probably because of its deep root system. The data on SOC dynamics from a 10 year experiment on rotation and grazing at Aleppo, Syria are shown in Table XI. Grazing had no significant effect in any of rotations on SOC or microbial biomass C, except in the wheat–Medicago rotation. Whereas the SOC content decreased in the wheat–fallow rotation, there was significant increase in the wheat–Medicago rotation *vis-à-vis* the wheat–medicago rotation. Total soil-C pool in the wheat–meadow rotation increased by 1·6 Mg ha^{-1} at the mean rate of 0·17 Mg ha^{-1} yr^{-1} in comparison with wheat–wheat rotation, and by 3·8 Mg ha^{-1} at the mean rate of 0·38 Mg ha^{-1} yr^{-1} in comparison with the wheat–fallow rotation. It is important to note that changes in SOC pool are slow to manifest in the WANA region and are detectable after about 10 years of conversion to a different management practice (White *et al.*, 1994; Ryan, 1998).

Despite the severe problem of soil erosion, the concept of conservation tillage is new to the region. Whether mechanized or animal driven, both primary and secondary tillage operations are used for seedbed preparation. Nonetheless, adoption of conservation tillage and mulch farming techniques can lead to improvement in the SOC pool. Experiments conducted in southern Spain by Murillo *et al.* (1998) demonstrated that conservation tillage was effective in increasing SOC content. Conservation tillage for sunflower cultivation was adopted in 1993. The SOC content in 1995 was 1·1 per cent for conservation tillage compared with 0·84 per cent for traditional tillage for 0–5 cm depth, and 0·76 per cent for conservation tillage and 0·75 per cent for traditional tillage for 5–30 cm depth. The SOC content in 1997 was 1·34 per cent for conservation tillage and 0·89 per cent for traditional tillage for 0–5 cm depth, and 0·76 per cent for both conservation tillage and traditional tillage for 5–30 cm depth. The increase in SOC content caused an overall increase in soil quality and productivity (Table XII).

Table XI. Effects of grazing, fallow and medic in the rotation on carbonates, organic and microbial biomass carbon in 0–20 cm depth after 10 years of the rotation cycle at Aleppo, Syria

Rotation	Carbonate C		Organic C			Microbial biomass C		
	Grazed (%)	Ungrazed (%)	Grazed (%)	Ungrazed (%)	Total C ($Mg\ ha^{-1}$)	Grazed (%)	Ungrazed (%)	Total C ($Mg\ ha^{-1}$)
Wheat–vetch	3·1	3·1	0·87	0·88	16·9	0·036	0·035	0·69
Wheat–lentil	2·8	3·0	0·85	0·84	16·4	0·036	0·035	0·68
Wheat–wheat	2·8	2·9	0·84	0·85	16·3	0·034	0·035	0·66
Wheat–chickpea	3·1	3·1	0·84	0·85	16·3	0·036	0·033	0·67
Wheat–fallow	2·8	2·8	0·77	0·75	14·7	0·033	0·030	0·60
Wheat–medic	2·8	2·8	0·93	1·0	18·5	0·038	0·036	0·61
SE	0·7	0·69	0·17	0·22	0·3	0·001	0·001	0·02

Source: adapted from Jenkinson *et al.*, 1999.

Table XII. Soil organic carbon and N contents in conservation and traditional tillage for sunflower cultivation under rainfed conditions in southern Spain

Year	Tillage	Depth (cm)	SOC (%)
1995	Conservation	0–5	1·12a
	Traditional	0–5	0·84b
	Conservation	5–30	0·76b
	Traditional	5–30	0·75b
1997	Conservation	0–5	1·34a
	Traditional	0–5	0·89b
	Conservation	5–30	0·76b
	Traditional	5–30	0·76

Source: modified from Murillo *et al.*, 1998. Figures in the column followed by the same letter are statistically similar.

The available literature thus shows that adoption of recommended practices of soil, crop and water management on croplands can enhance soil quality and improve SOC content. Despite the potential for enhancing SOC content, however, the rate of increase is likely to be low for drylands of the WANA region. Lal (1999) observed that potential rate (Mg C ha^{-1} yr^{-1}) of SOC sequestration for dryland ecosystem may be 0·1–0·2 for conservation tillage, 0·05–0·1 for mulch farming at the rate of 2–4 Mg of straw ha^{-1} yr^{-1}, 0·1–0·2 for application of farmyard manure on a regular basis, 0·05–0·1 for elimination of summer fallow, and 0·1–0·2 for integrated nutrient management and improved cropping systems. For a given ecoregion, however, the effects of different components listed above may not be additive. Therefore, the potential of SOC sequestration through adoption of RAPs may be 0·1–0·2 Mg C ha^{-1} yr^{-1} on undegraded prime land. Assuming that RAPs can be adopted on 60 Mha, the potential of soil C sequestration is as shown in Equation 3:

$$\begin{aligned}\text{SOC sequestration potential on prime agricultural land} &= (60\,\text{Mha}) \times (0{\cdot}1 - 0{\cdot}2\,\text{Mg C ha}^{-1}\,\text{yr}^{-1}) \\ &= 6 - 12\,\text{Tg C yr}^{-1} \qquad (3)\end{aligned}$$

THE POTENTIAL OF DRYLAND ECOSYSTEMS TO SEQUESTER CARBON

The data in Table XIII compares the soil C sequestration potential for the global dryland ecosystems and the WANA region. The mean potential of the global dryland ecosystems to sequester C is about 1000 Tg C yr^{-1} or 1 Pg C yr^{-1}. Squires *et al.* (1998) also estimated that drylands have the potential to reach an annual C sequestration rate of 1·0 Pg C yr^{-1}. In comparison, soils of the WANA region have a potential to reach an annual C sequestration rate of 0·2–0·4 Pg C yr^{-1} or about 20 per cent of the potential of the global dryland ecosystems. This potential rate of C sequestration can be maintained over a 25–50 year period, provided that coordinated efforts are made to adopt appropriate land use and recommended soil, water and crop management technologies.

Table XIII. The potential of the WANA region and the global dryland ecosystems to sequester C

	WANA region (this study)	Global dryland ecosystem (Lal, 2001)
Strategy	(Tg C yr^{-1})	(Tg C yr^{-1})
1. Desertification control	40–100	200–300
2. Reclamation of salt-affected soils	9–18	200–400
3. Agricultural intensification on undegraded soils	6–12	10–20
4. Fuel C offset	88–175	300–500
5. Soil C sequestration under biofuel planting	25–75	NA
Total	168–380	710–1220

There are numerous hidden costs of soil-C sequestration in agricultural ecosystems that need to be considered (Schlesinger, 1999). Agricultural intensification involves carbon-based inputs including tillage, herbicides, pesticides, fertilizers, and irrigation. Emission of C in all these inputs need to be considered in evaluating the net SOC sequestration. Careful analytical procedures are to be developed to assess the comparative C budget for traditional *vis-à-vis* the improved systems of crop/animal production. While the need for food production from agricultural systems cannot be overemphasized, the objective is to enhance production per unit consumption of C-based input.

DATA NEEDS TO REALIZE THE POTENTIAL

Soil C sequestration is a win-win strategy, because it has numerous ancillary benefits. It improves soil quality and enhances agronomic productivity. Improvement in soil quality reverses degradative trends and improves resilience of soil and ecosystems. Consequently, risks of soil erosion, soil degradation, and land desertification are minimized. Improvement in soil quality increases water and nutrient use efficiencies and minimizes risks of eutrophication of surface water and/or contamination of ground water. Afforestation and establishment of dedicated biofuel crops increase biodiversity.

Realization of the vast potential (0·2–0·4 Pg C yr^{-1} for the WANA region) through desertification control, soil restoration, and agricultural intensification is possible only if a coordinated effort is made to achieve the following:

(1) Obtain credible statistics on land use, farming systems and soil/crop management practices on regional basis.
(2) Obtain reliable data on the extent and rate (severity) of soil and vegetation degradation by different processes at regional and national scales.
(3) Understand soil-C dynamics in relation to the effect of land-use change and soil management, and in relation to degradative/restorative processes.
(4) Identify soil-specific practices of soil management and restorative technologies and assess the rate of SOC/SIC sequestration in relation to these practices.
(5) Understand the role of SIC in soil-C dynamics in relation to irrigation, biofertilizers, and other land use practices.
(6) Develop institutional support at all levels of technology transfer (e.g., farm, regional, national).
(7) Provide policy incentives to land managers to facilitate adoption of improved technology.
(8) Develop C trading mechanisms through its commodification as a farm product.

RELEVANCE TO THE KYOTO PROTOCOL

Article 3·3 of the Kyoto Protocol, established under the UNFCCC in December 1997, stating that the 'the net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period', provides for C credits due to land-use change. Further, Article 3·4 stating that 'additional human-induced activities related to changes in greenhouse gas emissions by sources and removal by sinks in the agricultural soils and land use change' makes provision for credit of C sequestered in agricultural soils. Thus, the soil-C sequestration potential in the WANA region is extremely relevant to implementation of the Kyoto Protocol. Further, C sequestration in soils and terrestrial ecosystems of the WANA region can be traded with Annex-I countries through the Clean Development Mechanism. At a modest price of $50 per ton, the economic worth of the annual C sequestration potential of 0·2–0·4 Pg C is US $10–20 billion. The agronomic, ecologic, and economic potential of soil-C sequestration thus cannot be overemphasized.

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