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Interactions between climate and desertification

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Abstract

Deserts are known to mankind, but the term desertification has always been an elusive concept. It is now defined in the United Nations Convention to Combat Desertification (UNCCD) as land degradation in the drylands (land falling within arid, semi-arid and dry sub-humid areas) resulting from various factors, including climatic variations and human activities. This definition, which is now being used worldwide to describe desertification and its impacts, leads to the need to consider carefully the two-way interactions between climate and desertification. Dramatic changes in agricultural practices during the last several decades are one of the main driving forces for land degradation in the drylands and examples of land degradation are given for several regions around the world. The effects of desertification on climate have been described mainly in terms of changes in land use and land cover leading to land degradation; overgrazing; biomass burning and atmospheric emissions; agriculture's contribution to air pollution; forest and woodland clearing and accelerated wind erosion; anthropogenic land disturbances and wind erosion; and the impact of irrigated agriculture on surface conditions in drylands. It is equally important to consider the impact of dryland climates on soils and vegetation and the impact of climate change on desertification. It is important to adopt uniform criteria and methods to assess desertification and encourage monitoring of dryland degradation in all the regions around the world. To better understand the interactions between climate and desertification, it is also important to identify the sources and sinks of dryland carbon, aerosols and trace gases in drylands.

Keywords: Land degradation; Land use and land cover changes; Overgrazing; Biomass burning and atmospheric emissions; Air pollution; Forest and woodland clearing; Wind erosion; Climate change

1. Introduction

Over the past three decades, there has been an increased awareness of the impact of growing human populations and the consequent pressures on environment and this has led to a number of important initiatives such as the Montreal Protocol on Substances that Deplete Ozone, the United Nations Conference on Environment and Development (UNCED) Plan of Action (Agenda 21) and the three Conventions arising from UNCED—the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and the United Nations Convention to Combat Desertification (UNCCD). Of the various anthropogenic actions that these initiatives address, desertification is perhaps the most visible as it affects more human lives than other anthropogenic actions. According to UNSO (1997), drylands are inhabited by approximately two billion people globally which represents 33% of the world's population. Several authors have suggested that desertification in the Sahel has caused a change in regional climate (Xue and Shukla, 1993).

Deserts are known to mankind and have been inhabited in some parts of the world by man since

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millennia. The term desertification, however, has always been an elusive concept as explained by Williams and Balling (1996) in their book on ‘‘Interactions of Desertification and Climate’’ which was sponsored by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). Several publications in the 1930s by Stebbing (1935, 1937a,b, 1938) referring to the encroaching Sahara gave the impression that the desert was advancing. Subsequently, Aubréville (1949) used the term desertification to describe the clearing and burning of forests in parts of Africa in order to cultivate land and the replacement of tropical rainforest by secondary savanna and scrub. UNEP (1977) defined desertification as ‘‘the diminution or destruction of the biological potential of land which can ultimately lead to desert-like conditions’’.

UNEP (1990) attributed all desertification to human activity by describing desertification as ‘‘land degradation in arid, semi-arid and dry sub-humid areas resulting from adverse human impact’’. After extended deliberations in the Intergovernmental Negotiating Committee (INCD) to prepare a Convention to Combat Desertification, desertification is now defined in the United Nations Convention to Combat Desertification (UNCCD) as ‘‘land degradation in the arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities’’ (this definition excludes the hyper-arid lands). Furthermore, UNCCD defines land degradation as a ‘‘reduction or loss, in arid, semi-arid, and dry sub-humid areas, of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical, and biological or economic properties of soil; (iii) long-term loss of natural vegetation’’. This definition, which is now being used worldwide to describe desertification and its impacts, leads to the need to consider carefully the two-way interactions between climate and desertification.

In describing these interactions, it is necessary on one hand to understand how human activities modify the surface characteristics and atmospheric composition of drylands and consider how these may influence local and regional dryland climates. Conversely, it is equally important to evaluate the impact of dryland climates on soils, ecosystems, water balance and human land use in the dryland regions. The objective of this paper is to provide a brief review of these interactions, building on the extensive treatment of the subject made by Williams and Balling (1996).

2. Problem of desertification and agriculture-related issues

In an assessment of population levels in the world’s drylands, the Office to Combat Desertification and Drought (UNSO) of the United Nations Development Programme (UNDP) showed that globally 54 million km^2 or 40% of the land area is occupied by drylands (UNSO, 1997). About 29.7% of this area falls in the arid region, 44.3% in the semi-arid region and 26% in the dry sub-humid region. A large majority of the drylands are in Asia (34.4%) and Africa (24.1%), followed by the Americas (24%), Australia (15%) and Europe (2.5%).

Estimates of the extent of desertification range widely. As opposed to the high estimates of 32.5 million km^2 by Dregne (1983) and 20 million km^2 by Mabbutt (1994), the GLASOD methodology of Oldeman and van Lynden (1998) gave a lower estimate of 11.4 million km^2. It is to be noted that the GLASOD estimate does not include the vegetation degradation on rangeland, but it is similar to that of UNEP (1991) for soil and vegetation degradation. For degradation on rangelands, UNEP (1991) gave an estimate of 25.8 million km^2.

According to UNCCD, over 250 million people are directly affected by desertification. In addition, some one billion people in over one hundred countries are at risk. These people include many of the world’s poorest, most marginalized, and politically weak citizens.

Long-term food productivity is threatened by soil degradation, which is now severe enough to reduce yields on approximately 16% of the agricultural land, especially cropland in Africa, Central America and pastures in Africa (Wood et al., 2000). Sub-Saharan Africa has the highest rate of land degradation, and the per capita food production continues to decrease. It is estimated that losses in productivity of cropping land in sub-Saharan Africa are in the order of 0.5–1% annually, suggesting productivity loss of atleast 20% over the last 40 years (Scherr, 1999). At the global level, it is estimated that the annual income lost in the areas immediately affected by desertification amounts to approximately US$ 42 billion each year.

According to UNCCD (2004), the consequences of desertification include undermining of food production, famines, increased social costs, decline in the quantity and quality of fresh water supplies, increased poverty and political instability, reduction in land's resilience to natural climate variability and decreased soil productivity.

3. Effect of desertification on climate

Desertification impacts climate in a number of different ways and following are some of the major processes involved.

3.1. Changes in land cover and land use leading to land degradation

Over the past several centuries, the world has witnessed unprecedented changes in the pace, magnitude and spatial extent of changes in the land surface use. Land use is defined through its purpose and is characterized by management practices such as logging, ranching, and cropping. Land cover is the actual manifestation of land use (i.e. forest, grassland, cropland) (IPCC, 2000).

3.1.1. Land cover changes

Land cover change is traditionally interpreted by distinguishing two different types: conversion and modification (Leemans and Zuidema, 1995). Land cover modification refers to the more subtle changes that affect the character of the land cover without changing its overall classification. Conversion refers to the complete replacement of one land cover type with another. Ramankutty and Foley (1999) estimated that since 1850, about 6 million km^2 of forests and woodlands and 4.7 million km^2 of savannas/grasslands/steppes were converted to croplands. Loss of vegetation cover is seen as one of the major causes of land degradation. It is estimated that, among other loss pathways, Africa loses its vegetation cover through annual deforestation rates of 0.7%, which is over twice the world average (FAO, 2000). The soil organic carbon pool to 1 m depth ranges from 30 tonnes ha^{-1} in arid climates to 800 tonnes ha^{-1} in organic soils in the cold regions (Lal, 2004). Conversion of natural to agricultural ecosystems causes depletion of soil organic carbon pool by as much as 60% in soils of temperate regions and 75% or more in cultivated soils of the tropics. Melack and MacIntyre (1992) have reported escalating soil erosion and siltation of water reservoirs and of coastal areas and in some cases, eutrophication of rivers and lakes, including Lake Victoria in East Africa, as a result of vegetation loss.

Sivakumar and Wills (1995) reported that 19% of Africa's forest and woodland have already been degraded. In Kenya alone, rural households account for 72% of total fuel wood consumption and trees are being cut at a rate that is 43% higher than sustainable yields (Muchena et al., 2005). These reports are alarming given that 70% of Kenya's forest resources are found in the arid and semi-arid lands. Using a dynamic simulation model of land use changes, Stéphanne and Lambin (2001) showed that in Burkina Faso, a phase of expansion of cropland, fallow and pastoral land was accompanied by deforestation in 1970s and early 1980s and the first signs of land degradation in cropland appeared in 1991.

Cardille and Foley (2003) used census and satellite records to develop maps of the distribution and abundance of major agricultural land uses across 4.5×10^8 ha of Brazilian Amazonia in 1980 and 1995. Results indicate an overall expansion of 7.0×10^6 ha in total agricultural area in Brazilian Amazonia between 1980 and 1995. The net change during this period is estimated for three different land use types: croplands (an increase of 0.8×10^6 ha), natural pastures (a decrease of 8.4×10^6 ha), and planted pastures (an increase of 14.7×10^6 ha).

3.1.2. Land use changes

Land use changes include the manner in which the land is manipulated and the intent underlying that manipulation (Turner et al., 1995). In the context of this paper, manipulation of land refers to the specific way in which humans use vegetation, soil and water for food production e.g. the use of fertilizers, pesticides and irrigation for mechanized cultivation (Verburg et al., 2000). There is evidence from several parts of the world that extensive land use changes have left large areas exposed to erosion. For example, in the Western Mediterranean region, accelerated erosion in the hilly country caused by new agricultural systems resulted in increased sedimentation rates recorded in the deltas of eastern Andalucia rivers: about 17 mm $year^{-1}$ in the Adra and 80 mm $year^{-1}$ in the Andarax during the 18th century (Hoffman, 1988). Conversion of forest to grassland the Western Mediterranean region has been shown to double the specific runoff and increase the sediment yield by 16 times (Puigdefábregas and Alvera, 1986).

3.2. Climatic consequences associated with land use/land cover changes

As Tolba and El-Kholy (1992) described, land use/land cover changes are the primary source of land degradation and determine, in part, the vulnerability of places and people to climatic, economic and socio-political perturbations (Kasperson et al., 1995). Land use and land cover changes contribute to anthropogenic climate change through a variety of processes (Marland et al., 2003). These include the growth or degradation of surface vegetation, which produces changes in the global atmospheric concentration of CO_2; and changes in the land surface, which affect regional and global climate by producing changes in the surface energy budgets.

Land surface is an important part of the climate system. Changes in surface energy budgets resulting from land cover change can have a profound influence on the Earth's climate. To the extent that man's agricultural and pastoral activities increased the stress on plant cover, they might be a factor in the increase of surface albedo, thus contributing to the persistence of droughts. Charney (1975) first presented a theory as to how a reduction in vegetation might feedback to produce a decrease in rainfall. In this hypothesis, the increase in albedo associated with an imposed reduction in vegetation cover leads to enhanced radiative cooling. This in turn is balanced by enhanced descent, reduced rainfall and a consequent decrease in the potential vegetation cover that can be sustained. The hypothesis was subsequently tested in numerical simulations with a general circulation model (Charney et al., 1977). Courel et al. (1984) found that dry season albedo in the Sahel declined from a maximum close to 0.30 in 1973 to values close to 0.20 in 1979, which was consistent with the changes in plant cover determined by analysis of spectral changes in the Landsat multispectral scanner data and field studies. The biosphere-albedo feedback theory underpins the view that local land use practices inherently tend towards land degradation and loss of productivity in the Sahelian rangelands (Sinclair and Fryxell, 1985). Analysing the role of human interference in the climatic trends in West Africa, Adefolalu (1982) concluded that the drying trend in this area is a consequence (rather than a cause) of the man-induced desertification. It was argued that drought only aggravated a bad situation because of its persistence during the 1969–1973 period. Dirmeyer and Shukla (1996) used an atmospheric general circulation model with realistic land-surface properties to investigate the climatic effect of doubling the extent of Earth's deserts and most regions showed a positive correlation between decreases in evapotranspiration and resulting precipitation. It was shown that Northern Africa suffers a strong year-round moisture deficiency while southern Africa has a somewhat weaker year-round water deficit. Some regions, particularly the Sahel, showed an increase in surface temperature caused by decreased soil moisture and latent-heat flux.

However, such conventional views on land degradation are widely challenged on the basis of detailed, long term field studies in northern Nigeria (Mortimore, 1998) and elsewhere (Ramisch, 1999).

The interaction between land surface and the atmosphere involves multiple processes and feedbacks, all of which may vary simultaneously. It is frequently stressed (Henderson-Sellers et al., 1993; McGuffie et al., 1995; Sud et al., 1996) that the changes of vegetation type can modify the characteristics of the regional atmospheric circulation and the large-scale external moisture fluxes. Following deforestation, surface evapotranspiration and sensible heat flux are related to the dynamic structure of the low-level atmosphere. Zhang et al. (1996) traced changes due to tropical deforestation using a number of statistical measures and analyzed the underlying radiative and turbulent flux interactions. These changes in fluxes within the atmospheric column could influence the regional, and potentially, global-scale atmospheric circulation. Changes in forest cover in the Amazon basin affect the flux of moisture to the atmosphere, regional convection, and hence regional rainfall (Lean and Warrilow, 1989). More recent work shows that these changes in forest cover have consequences far beyond the Amazon basin (Werth and Avissar, 2002). Use of a numerical simulation model to study the interactions between convective clouds, the convective boundary layer and a forested surface by Garrett (1982) showed that surface parameters such as soil moisture, forest coverage, and transpiration and surface roughness may affect the formation of convective clouds and rainfall through their effect on boundary-layer growth.

Land use and land cover changes influence carbon fluxes and GHG emissions (Houghton, 1995; Braswell et al., 1997) which directly alter atmospheric composition and radiative forcing properties. They also change land-surface characteristics and, indirectly, climatic processes (Bonan, 1997; Claussen, 1997). Observations during HAPEX-Sahel suggested that a large-scale transformation of fallow savannah into arable crops like millet, may lead to a decrease in evaporation (Gash et al., 1997). Land use and land cover change is an important factor in determining the vulnerability of ecosystems and landscapes to environmental change (Peters and Lovejoy, 1992). Finally, several options and strategies for mitigating GHG emissions involve land cover and changed land use practices (IPCC, 1996).

Since the industrial revolution, global emissions of carbon (C) due to land use change and soil cultivation are estimated at 136 ± 55 Pg (Pg = petagram = 10^{15}). Emissions due to land use change include those by deforestation, biomass burning, conversion of natural to agricultural ecosystems, drainage of wetlands and soil cultivation. Depletion of soil organic C (SOC) pool have contributed 78 ± 12 Pg of C to the atmosphere. Some cultivated soils have lost one-half to two-thirds of the original SOC pool with a cumulative loss of 30–40 Mg C ha^{-1} (Mg = megagram = 10^6). The depletion of soil C is accentuated by soil degradation and exacerbated by land misuse and soil mismanagement (Lal, 2004).

3.3. Overgrazing

In the Sahel, land cover includes grazing land interspersed with cropland mosaic and woodland, all representing habitat for wild and domesticated herbivores, and collectively termed rangelands (Pratt and Gwynne, 1977). Rangelands therefore include pastoral grazing lands, smallholder farmland such as the Sahelian crop and fallow mosaics, and savanna protected areas. The vegetation formations shift between grassland, bush, woodland and cropland, depending upon biophysical factors of climatic fluctuations, fire, grazing and browsing pressures, and successional stage, as well as anthropogenic factors of changing land use and population densities (Homewood and Brockington, 1999). Sub-Saharan African rangelands are undergoing land degradation and desertification, meaning an irreversible decline in productivity, as a result of climate change combined with overgrazing, overstocking, and damaging soil management practices including nutrient mining.

Overgrazing in rangelands is widely considered to be a major cause of desertification in rangelands due to depletion of grass and shrub cover and accelerated loss of top soil. When soil is trampled and compacted by cattle, it can lose its ability to support plant growth and to hold moisture, resulting in increased evaporation and surface run-off. Locally severe overgrazing can aggravate the impact of drought and desertification by modifying soil microclimate, altering soil–water–plant relationships and exposing bare soil to erosion.

3.4. Biomass burning and atmospheric emissions

Uncontrolled wildfires and prescribed fires occur in all vegetation zones of the world. It is estimated that fires annually affect 1015 million ha (M ha) of boreal and temperate forest and other lands, 2040 M ha of tropical rain forests and up to 500 M ha of tropical and subtropical savannas, woodlands, and open forests. About 80% of the biomass burning now occurs in the intertropical zone, of which nearly half is from agricultural burning and use of wood for fuel. Most of the fires are deliberately started by humans. Biomass burning is a common practice in the tropics and subtropics. It affects Africa all year round, but particularly prevalent during the dry season.

The size of the soil organic carbon pool doubles that present in the atmosphere and is about two to three times greater than that accumulated in living organisms in all Earth's terrestrial ecosystems (González-Pérez et al., 2004). In such a scenario, one of the several ecological and environmental impacts of fires is that biomass burning is a significant source of greenhouse gases responsible for global warming. Ito and Penner (2004) estimated global biomass burning emissions at 1428 Tg C, while Hoelzemann et al. (2004) estimated it at 1741 Tg C. Both these estimates substantially lower than the 2600 Tg C emissions estimated by van der Werf et al. (2004). Several factors such as burning area, type of fuel available for burning and depth of burning influence the emission estimates. For example, Kasischke and Penner (2004) concluded that current approaches for estimating global emissions are limited by accurate information on area burned and fuel available for burning. In their papers, Soja et al. (2004a,b) explored how assumptions regarding the depth of burning of the ground layer affect total emissions from boreal forests in eastern Russia. They showed that moderate level of ground-layer burning increases total carbon emissions by 66% and high level of ground-layer burning increases it by 270%.

Research carried out by Crutzen et al. (1979) and Seiler and Crutzen (1980) first brought to light the role that biomass burning plays in determining the atmospheric concentration of a number of important atmospheric trace gases, as well as particulate matter. These initial studies provided the catalyst for extensive research over the past two decades to improve estimates of emissions from global biomass burning. Globally, biomass burning is estimated to produce 40% of the carbon dioxide, 32% of the carbon monoxide, 20% of the particulates, and 50% of the highly carcinogenic poly-aromatic hydrocarbons produced by all sources (Levine, 1990).

Using the emission ratios obtained in their study and estimating the amount of methane emissions from biomass burning, Gupta et al. (2001) suggested that nearly 0.99 Tg of methane is emitted annually from the practice of shifting cultivation in India.

Smith et al. (2001) present a new inventory of global sulfur dioxide emissions from anthropogenic activities for the years 1980–2000. Emissions were estimated in 11 world regions using country-level emissions inventories and regional fossil fuel sulfur content information. Estimated global emissions in 1990 are 72 Tg S with an estimated uncertainty of ±8% due to random errors with additional systematic errors that suggest that true emissions may be higher than this central value. It was estimated that 3% of 1990 world emissions are from biomass burning.

The influence of fire on soil characteristics (soil–water content, soil compaction, soil temperature, infiltration ability, organic matter, pH, exchangeable Ca, Mg, K, Na and extractable P) of a semi-arid southern African rangeland was quantified over two growing seasons (2000/2001–2001/2002) following an accidental fire (Snyman, 2003). The decrease in basal cover due to fire (head fires) exposed the soil more to the natural elements and therefore to higher soil temperatures and soil compaction in turn leading to lower soil–water content and a decline in soil infiltrability.

3.5. Agriculture's contribution to air pollution

Public attention tends to focus on the more visible signs of agriculture's impact on the environment, whereas it seems likely that the non-visible or less obvious impacts of air pollution cause the greatest economic costs. Huge amounts of air pollution are produced worldwide by the annual burning of three billion metric tonnes of biomass such as wood, leaves, trees, grass and trash (Abelson, 1994). Biomass burning represents the largest source of air pollution in many rural areas of the developed and developing world.

Outdoor fires, such as wildfires and prescribed burnings, can emit substantial amounts of particulate matter and other pollutants into the atmosphere. In Texas, an inventory of forest, grassland and agricultural burning activities revealed that fires consumed vegetation on 0.65 and 0.69 million ha of land, in 1996 and 1997, respectively (Dennis et al., 2002). Emissions from the fires were estimated based on survey and field data on hectares burned and land cover and literature data on fuel consumption and emission factors. For fine particulate matter, however, the annual emission estimates were 40,000 tonnes year^{-1}, which is likely to represent a significant fraction of the State's emission inventory, especially in the counties where the emissions are concentrated.

Stubble from wheat, corn, rice and other crops is often burned away in the fields. A 5-year study in a rice growing area of Japan reported that the average number of childhood asthma hospital visits were more than double during the rice burning months of September and October as compared to the rest of the year (Torigoe, 2000).

Worldwide, huge amounts of biomass are burned in tropical rain forests in South America, Africa and Malaysia/Indonesia to make room for agricultural crops. The stubble of tropical crops is also often burned to form a ‘‘slash and burn’’ agriculture which depletes the soil rapidly and forces farmers to abandon fields after several years of burning. Over the past 10 years, huge areas of Indonesian and Malaysian rainforests have been burned to make room for farming operations. The smoke from these huge fires has traveled for hundreds of miles to Singapore and the Philippines. In September 1997, all 28 Malaysian air quality stations recorded air concentrations of particulates smaller than 10 μm (PM10) above 150 μg m^{-3}. In the Kuala Lumpur Hospital, respiratory admissions were 912 in June 1997, but rose more than five-fold to over 5000 in during the heavy forest burning month of September 1997 (Awang, 2000).

The emission of mercury (Hg) from biomass burning was investigated in laboratory experiments and the results confirmed in airborne measurements on a wildfire in Canada (Friedli et al., 2003). Replicate burns of dry Ponderosa needles indicated a linear relationship between emitted mercury and fuel mass loss. Mercury released from fuel could be accounted for as gaseous and particulate mercury in the smoke. The mercury content of regionally collected fuels varied between 14 and 70 ng g^{-1} on a dry mass (dm) basis.

Biomass burning and soil erosion are estimated to be the major sources of Hg for the Lake Victoria, East Africa (Campbell et al., 2003) and probably constitute a larger source of Hg than gold mining in Tanzania.

3.6. Forest and woodland clearing and accelerated erosion

Large areas of world's forests, which have served human needs for centuries in the past, have been converted to other uses or severely degraded. The Global Forest Resource Assessment (FAO, 2001) showed that the world's forests covered 3869 M ha in 2000, about 30% of the world's land area. The net change in forest area was −9.4 M ha year^{-1}, representing the difference between a deforestation rate of 14.6 M ha year^{-1} of natural forests and an expansion of 5.2 M ha year^{-1} of natural forests and forest plantations. Most of the forest losses were in the tropics. FAO (2001) estimates that almost 1% of the tropical forest is being lost each year. The direct conversion of forests to permanent agriculture or other land uses was much more prevalent than gradual intensification of shifting agriculture. Bruinsma (2003) estimated that a good part of the 3.8 M ha of annual net new agricultural land over the period to 2030 will probably come from forest conversion. A high proportion will have steep slopes and will be in zones with high rainfall, so the water erosion risk will be high unless suitable management techniques are adopted.

If the soil surface is left bare through clearing for agriculture, the erosive impact of early season convective rains can increase erosion by a factor of 50 or more. Accelerated soil erosion affects the C pool and fluxes because of breakdown of soil aggregates, exposure of C to climatic elements, mineralization of organic matter in disrupted aggregates and redistributed soil, and transport of sediments rich in soil organic carbon downslope to protected areas of the landscape.

3.7. Anthropogenic land disturbances and wind erosion

In regions where long dry periods associated with strong seasonal winds occur regularly, the vegetative cover of the land does not protect the soil sufficiently, and the soil surface is disturbed due to inappropriate management practices, wind erosion usually is a serious problem. Farming operations that facilitate wind erosion and dust emissions include plowing, leveling beds, planting, weeding, seeding, fertilizing, mowing, cutting, baling, spreading compost or herbicides and burning fields (Nordstrom and Hotta, 2004). Human-induced change is by far the most significant factor in the alarming increase of dust storms in some regions.

It has been estimated that in the arid and semi-arid zones of the world, 24% of the cultivated land and 41% of the pasture land are affected by moderate to severe land degradation from wind erosion (Rozanov, 1990). The world-wide total annual production of dust by deflation of soils and sediments was estimated to be 61–366 million tonnes. For Africa, it is estimated that more than 100 million tonnes of dust per annum is blown westward over the Atlantic (Middleton et al., 1986).

Losses of desert soil due to wind erosion are globally significant (Pye, 1987). Past policies on land use and the promotion of farming systems that were unsustainable were the root cause of most disasters. There is evidence that dust storms have become more frequent as a result of human activities in semi-arid lands (Middleton et al., 1986). For example, in China serious wind erosion occurs in the semi-arid region, where overgrazing and ploughing of rangeland have dramatically increased since the beginning of the 20th century (Zhu and Wang, 1993). Every year desert encroachment caused by wind erosion buries 210,000 ha of cropland in China (PRC, 1994). Ci (1998) showed the annual changes of the frequency of strong and extremely strong sandstorms in China as follows: 5 times in the 1950s, 8 times in the 1960s, 13 times in the 1970s, 14 times in the 1980s, 20 times in the 1990s.

In the West African Sahel, rapid population growth, at annual rates of 3% during recent decades, has increased demand for food. Instead of intensifying farming systems, for instance by using mineral fertilizers, farmers have tried to enhance production by expanding the cropped area. The previously sustainable fallow system has broken down, yields have declined, and more marginal land, which used to be communal grazing land, is now cropped. Consequently, over-exploitation has resulted in land degradation, or desertification, on a large scale.

According to Khatteli (1998), the deposition of sand over olive crops in northern Africa resulted from excessive cultivation of soil with disk harrow that pulverised the soil and made it more vulnerable to wind erosion. This is manifested by the disappearance of olive crops where the deflation and formation of movable sand dunes occurred or where the sand deposition occurred.

The very fine fraction of soil-derived dust has significant forcing effects on the radiative budget. Dust particles are thought to exert a radiative influence on climate directly through reflection and absorption of solar radiation and indirectly through modifying the optical properties and longevity of clouds. Depending on their properties and in what part of the atmosphere they are found, dust particles can reflect sunlight back into space and cause cooling in two ways. Directly, they reflect sunlight back into space, thus reducing the amount of energy reaching the surface. Indirectly, they act as condensation nuclei, resulting in cloud formation (Pease et al., 1998). Clouds act as an "*atmospheric blanket*", trapping long wave radiation within the atmosphere that is emitted from the earth. Thus, dust storms have local, national and international implications concerning global warming. Climatic changes in turn can modify the location and strength of dust sources.

3.8. Impact of irrigated agriculture on surface conditions in drylands

The irrigated area in the world has increased 50-fold during the last three centuries i.e. from 5 M ha in 1700 to 255 M ha in 2000 (Lal, 2001). About 30% of all irrigated lands are considered to be degraded to varying degrees. Inadequate drainage and ineffective leaching of the soil, can cause problems of water logging and salinization which are becoming increasingly frequent. Salt accumulation is governed by the water balance of the area, in particular by the ratio of evapotranspiration to drainage. Man-induced salt accumulation occurred in previous salt-free soils due to errors in designing and constructing irrigation projects (Zalidis et al., 2002). A secondary and equally incidious problem is the dispersion of sodic soils leading to a reduction in soil infiltration capacity and permeability (Williams and Balling, 1996).

Currently, 45 M ha or 19.5% of the irrigated area are salt-affected. Salinization is a severe problem in China, India, Pakistan, and in countries of Central Asia (Babaev, 1999). Salinization is also a problem in southwestern USA, northern Mexico and dry regions of Canada (Balba, 1995). It is reported that about 25% of the irrigated land in Mediterranean Europe suffers from soil salinization (Szabolcs, 1990).

Progressive salinization leads to increased albedo over salt pans and dry salt lakes as compared to the surrounding bare or sparsely vegetated sand dunes which leads to a greater contrast in surface temperatures. Tapper (1991) recorded albedo values of nearly 60% on a dry salt lake surface as opposed to 32% over adjacent dunes. The result was a day temperature of 40 °C on sand versus 24 °C on salt crust and a night temperature of 0.4 °C on sand and 8 °C on salt. The resulting changes in airflow due to nocturnal air flow convergence and daytime divergence could accelerate wind erosion and dust deflation.

4. Impact of dryland climates on soils and vegetation with specific reference to desertification

Extended droughts in certain arid lands have initiated or exacerbated desertification. In the past 25 years, the Sahel has experienced the most substantial and sustained decline in rainfall recorded anywhere in the world within the period of instrumental measurements (Hulme and Kelly, 1997).

The Sahelian droughts in the early 1970s were almost unique in their severity and were characterized as "the quintessence of a major environmental emergency" (Raynaut et al., 1997) and their long-term impacts are now becoming clearer. A coupled surface–atmosphere model indicates that – whether anthropogenic factors or changes in Sea Surface Temperature (SST) initiated the Sahel drought of 1968–1973 – permanent loss of Sahel savanna vegetation would permit drought conditions to persist (Wang and Eltahir, 2000). The effect of drought, reducing soil moisture and thus evaporation and cloud cover, and increasing surface albedo as plant cover is destroyed, is generally to increase ground and near-surface air temperatures while reducing the surface radiation balance and exacerbating the deficit in the radiation balance of the local surface–atmosphere system. This entails increased atmospheric subsidence and consequently further reduced precipitation.

4.1. Impacts on vegetation

Climate exerts a strong influence over dryland vegetation type, biomass and diversity. Precipitation and temperature determine the potential distribution of terrestrial vegetation and constitute principal factors in the genesis and evolution of soil. Precipitation also influences vegetation production, which in turn controls the spatial and temporal occurrence of grazing and favours nomadic lifestyle. Dryland plants and animals display a variety of physiological, anatomical and behavioural adaptations to moisture and temperature stresses brought about by large diurnal and seasonal variations in temperature, rainfall and soil moisture.

4.2. Impacts on soils

Soil organic carbon (SOC) stocks result from the balance between inputs and decomposition of soil organic matter (SOM). Predicted increased air and soil temperatures can be expected to increase the mineralization rate of SOM fractions that are not physically or chemically protected. The degree of protection of SOM varies with several soil-specific factors, including structure, texture, clay mineralogy, and base cation status. This may lead in the long term to negative effects on structural stability, water-holding capacity, and the availability of certain nutrients in the soil (Reilly et al., 1996).

Land management will continue to be the principal determinant of SOM content and susceptibility to erosion during the next few decades, but changes in vegetation cover resulting from short-term changes in weather and near-term changes in climate are likely to affect SOM dynamics and erosion, especially in semi-arid regions (Valentin, 1996; Gregory et al., 1999).

Williams and Balling (1996) provided a nice description of the nature of dryland soils and vegetation and the manner in which climate affects the soils and vegetation. The generally high temperatures and low precipitation in the drylands lead to poor organic matter production and rapid oxidation. Low organic matter leads to poor aggregation and low aggregate stability leading to a high potential for wind and water erosion.

The severity, frequency, and extent of erosion are likely to be altered by changes in rainfall amount and intensity and changes in wind (Gregory et al., 1999). Models demonstrate that rill erosion is directly related to the amount of precipitation but that wind erosion increases sharply above a threshold wind speed. In the U.S. corn belt, a 20% increase in mean wind speed greatly increases the frequency with which the threshold is exceeded and thus the frequency of erosion events (Gregory et al., 1999). Thus, the frequency and intensity of storms would have substantial effects on the amount of erosion expected from water and wind (Gregory et al., 1999). Different conclusions might be reached for different regions. Thus, before predictions can be made, it is important to evaluate models for erosion and SOM dynamics (Smith et al., 1997). By reducing the water-holding capacity and organic matter contents of soils, erosion tends to increase the magnitude of nutrient and water stress. Hence, in drought-prone and low-nutrient environments such as marginal croplands, soil erosion is extremely likely to aggravate the detrimental effects of a rise in air temperature on crop yields.

The high evapotranspiration which greatly exceeds precipitation leads to accumulation of salts on soil surface. Soils with natric horizon are easily dispersed. The low moisture levels lead to limited biological activity. Structural crusts/seals formed by raindrop impact which could decrease infiltration, increase runoff and generate overland flow and erosion.

4.3. Climate change and desertification

Human activities – primarily burning of fossil fuels and changes in land cover – are modifying the concentration of atmospheric constituents or properties of the Earth's surface that absorb or scatter radiant energy. In particular, increases in the concentrations of greenhouse gases (GHGs) and aerosols are strongly implicated as contributors to climatic changes observed during the 20th century and are expected to contribute to further changes in climate in the 21st century and beyond. These changes in atmospheric composition are likely to alter temperatures, precipitation patterns, sea level, extreme events, and other aspects of climate on which the natural environment and human systems depend.

According to IPCC (2003), ecosystems are subject to many pressures (e.g. land use change, resource demands, population changes); their extent and pattern of distribution is changing, and landscapes are becoming more fragmented. Climate change constitutes an additional pressure that could change or endanger ecosystems and the many goods and services they provide. Soil properties and processes – including organic matter decomposition, leaching, and soil water regimes – will be influenced by temperature increase (high confidence). Soil erosion and degradation are likely to aggravate the detrimental effects of a rise in air temperature on crop yields. Climate change may increase erosion in some regions, through heavy rainfall and through increased windspeed.

CO_2-induced climate change and desertification remain inextricably linked because of feedbacks between land degradation and precipitation. Climate change might exacerbate desertification through alteration of spatial and temporal patterns in temperature, rainfall, solar isolation, and winds. Several climate models suggest that future global warming may reduce soil moisture over large areas of semi-arid grassland in North America and Asia (Manabe and Wetherald, 1986). This climate change is likely to exacerbate the degradation of semi-arid lands that will be caused by rapidly expanding human populations during the next decade. Emanuel (1987) predicted a 17% increase in the world area of desert land during the climate changes expected with a doubling of atmospheric CO_2 content. Any shift to a greater area of arid land potentially represents a permanent loss in the productive capacity of the biosphere on which all life depends.

Water resources are inextricably linked with climate, so the prospect of global climate change has serious implications for water resources and regional development (Riebsame et al., 1995). Climate change – especially changes in climate variability through droughts and flooding – will make addressing these problems more complex. The greatest impact will continue to be felt by the poor, who have the most limited access to water resources. The impact of changes in precipitation and enhanced evaporation could have profound effects in some lakes and reservoirs. Studies show that, in the paleoclimate of Africa and in the present climate, lakes and reservoirs respond to climate variability via pronounced changes in storage, leading to complete drying up in many cases. Furthermore, these studies also show that under the present climate regime several large lakes and wetlands show a delicate balance between inflow and outflow, such that evaporative increases of 40%, for example, could result in much reduced outflow. Feddema (1998, 1999) has evaluated the impacts of soil degradation and global warming on water resources for Africa. All major watersheds are affected by global warming; although the trend is toward drying in most locations, there are significant differences in watershed-level responses, depending on timing and distribution of rainfall, as well as soil water-holding capacity. Soil water-holding capacity is modified by the degree of soil degradation.

Soils exposed to degradation as a result of poor land management could become infertile as a result of climate change. Temperature increases would have negative impacts on natural vegetation in desert zones. Plants with surface root systems, which utilize mostly precipitation moisture, will be vulnerable. Many watersheds in Asia already are stressed by intensive use of the land and other resources and by inhospitable climate (especially in arid and semi-arid Asia), beyond their ability to adequately supply water, prevent floods, and deliver other goods and services. In the absence of appropriate adaptation strategies, these watersheds are highly vulnerable to climate change.

The frequency of episodic transport by wind and water from arid lands is also likely to increase in response to anticipated changes in global climate (Manabe and Wetherald, 1986). Sample plots in Niger lost 46 tonnes ha^{-1} in just four windstorms in 1993 (Sterk et al., 1996), releasing 180 ± 80 kg ha^{-1} $year^{-1}$ of soil carbon (Buerkert et al., 1996). Moreover, increased wind erosion increases wind-blown mineral dust, which may increase absorption of radiation in the atmosphere (Nicholson and Kim, 1997).

5. Conclusions

There is considerable evidence from different parts of the world that dramatic changes in agricultural practices during the last several decades are one of the main driving forces for land degradation in the drylands. It is clear that these human-induced changes have a significant influence on the energy balance of both land and atmosphere. Changes in both land use and land cover have contributed to land degradation in terms of both surface albedo and soil moisture impacts. Other anthropogenic activities such as overgrazing, biomass burning, and improper management of irrigation clearly contribute to land degradation and carry consequences for climate. Dryland climate carries a major impact on soils and vegetation since the soils are inherently weak and are susceptible to both wind and water erosion. There is now a much greater understanding of the role of climate change and it’s impacts on drylands. Warming of the drylands and the predicted changes in precipitation carry implications for sustainable agriculture in drylands over the next several decades.

As Dumanski and Pieri (2000) explained, monitoring the impacts of agriculture on the environment is much more difficult than monitoring other sectors. Hundreds of millions of private farmers, large and small, are stewards of the globe’s land resources, and monitoring the impacts of their land use decisions is a major undertaking. Nonetheless, there is an urgent need to monitor the interactions between desertification and climate. Arid lands are likely to play a greater role in global biogeochemical function in the future as the area of arid land is expected to increase, along with episodic, long range transport of soil resources (Schlesinger et al., 1990).

It is important to adopt uniform criteria and methods to assess desertification and encourage monitoring of dryland degradation in all the regions around the world. To better understand the interactions between climate and desertification, it is also important to identify the sources and sinks of dryland carbon, aerosols and trace gases in drylands. This can be effectively done through regional climate monitoring networks. Such networks could also help enhance the application of seasonal climate forecasting for more effective dryland management.

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