LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. (2011)
DOI: 10.1002/ldr.1151

A FRAMEWORK FOR NATIONAL ASSESSMENT OF LAND DEGRADATION IN THE DRYLANDS: A CASE STUDY OF SOMALIA

C. T. OMUTO[1]*, Z. BALINT[2] AND M. S. ALIM[2]
[1]*Department of Environmental and Biosystems Engineering, University of Nairobi, PO Box 30197-00100, Nairobi, Kenya*
[2]*FAO-SWALIM, PO Box 30477-00100, Naiorbi, Kenya*

Received: 7 December 2010; Revised: 28 April 2011; Accepted: 5 September 2011

ABSTRACT

Land degradation is a gradual, negative environmental process that is accelerated by human activities. Its gradual nature allows degradation to proceed unnoticed, thus reducing the likelihood of appropriate and timely control action. Presently, there are few practical frameworks to help countries design national strategies and policies for its control. The study presented here developed a framework for the national assessment of land degradation. This framework is envisaged to support governments in formulating policies on land degradation. It uses time-series remote sensing data to identify the rate and extent of land degradation, local experts to identify prevalent degradation types and drivers of the degradation and field observations to validate the overall assessment. Its simplicity, use of freely downloadable input data and self-triangulation of the assessment methods make it suitable for rapid assessment of land degradation on a national scale. It was tested in Somalia, where it exhibited accuracy greater than 60 per cent when assessing land degradation. This framework is relevant for designing national strategies and policies that address land degradation and provides an opportunity for accurate identification of areas to target with comprehensive local assessment. Testing of the framework in Somalia showed that about one-third of the country was degraded because of loss of vegetation cover, topsoil loss and to the decline of soil moisture. Overgrazing, excessive tree cutting and poor agronomic practices in agricultural areas were identified as the primary drivers of the country's land degradation. These drivers are encouraged by the prevailing communal land tenure practices, poor governance and civil war. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: land degradation; drylands; modelling; Somalia; assessment framework

INTRODUCTION

Land degradation is a negative environmental process that has been defined and viewed in many different ways by different researchers. Some have defined it as a general reduction of the (agricultural) productive potential of land (Foster, 2006) or as a long-term decline in ecosystem functions (Bai *et al*., 2008). Others describe it as a general term describing how land resources have negatively changed because of human activities over time (UNEP, 1992; Stocking and Murnaghan, 2001). Land degradation has also been defined as a form of land cover modification because of human impacts under climatic variations (Diouf and Lambin, 2001). Despite these differences in specific terms, there is a general agreement on the features of land degradation: it causes a decline of the land resources' capacity to perform their functions (e.g. production of energy and food, filtration of water and air, supplying habitat, etc.); it is a gradual, negative environmental process; and it is accelerated by negative human activities. Land degradation, in most cases, begins with subtle characteristics and later develops observable features as it advances. This gradual nature makes it to progress unnoticed in many parts of the world until the degradation is quite advanced. Consequently, attempts to control land degradation have been undertaken when the degradation is advanced and is relatively expensive and cumbersome to manage. Sometimes, the attempts fail to control land degradation. These difficulties explain, in part, why the degradation continues to be a global challenge (Dregne, 2002; Nachtergaele and Licona-Manzur, 2006). Other factors, such as a lack of policies and guidelines for combating land degradation, also contribute to its worldwide spread (Stefano, 1999; Bai *et al*., 2008). There are several countries without clear policies in addressing land degradation (Eklund, 1991; Lestrelin and Giordano, 2006; Lestrelin, 2010). They lack national strategies for control of land degradation and guidelines for protecting non-degraded areas from degradation. Research is therefore needed to support these countries in their development of national strategies for combating and monitoring land degradation.

There are various methods in the literature for assessing different stages of land degradation at different spatial and temporal scales. Expert opinions and field measurements of degradation are examples of methods that can be used to target advanced land degradation (Oldeman *et al*., 1991;

---

*Correspondence to: C. T. Omuto, Department of Environmental and Biosystems Engineering, University of Nairobi, PO Box 30197-00100, Nairobi, Kenya.
E-mail: thineomuto@yahoo.com

Stocking and Murnaghan, 2001; Sonneveld, 2003; Thiam, 2005). These methods target advanced degradation because, at this stage, the degradation has manifested features that are easily identified. The expert opinion approach is often applied at coarse spatial scales, and measurements of observable degradation features in the field are carried out at the local level. Application of these approaches has recently been improved by the use of remote sensing (Wessels *et al*., 2007; Bai *et al*., 2008; Gao and Liu, 2008; Metternicht *et al*., 2009). Remote sensing has a higher spectral resolution than the human eye for detecting some degradation features. Moreover, it can be implemented at multiple spatial and temporal scales, which allows it to detect the changing characteristics of land degradation that are not easily determined by expert opinion and field measurements. There are also literature reports of land degradation assessment methods that can detect early stages of the degradation. Such assessments include temporally repeated laboratory analysis of soil and plant properties and modelling of soil and vegetation degradation (Diouf and Lambin, 2001; Shepherd *et al*., 2003; Symeonakis and Drake, 2004; Omuto, 2008). Although these assessments have been reported to be accurate in detecting incipient degradation characteristics, they still have certain application challenges. These challenges include a lack of simplicity for the end-users, a high demand for the input data, a low repeatability in independent areas and a loss of accuracy at large assessment scales (Omuto, 2008). The literature also reports another group of assessment methods that use time-series crop productivity trends (Lal *et al*., 1998; Dregne, 2002). Here, the approach is based on observing the time-series trends of crop productivity against changing land degradation characteristics. However, the method is least favoured because of a lack of clear linkage between crop productivity and land degradation (Lal *et al*., 1998). The use of net primary productivity indicators obtained via remote sensing is a recent attempt to improve this linkage (Wessels *et al*., 2008; Prince *et al*., 2009).

The existing methods for land degradation assessment have various characteristics that make them suitable for specific applications. Individual methods can still be combined to maximize their strengths to support countries that need help in developing national strategies for controlling land degradation. The objective of this study was to integrate some of the above methods for assessing land degradation at the national scale to produce a versatile framework for assessing national land degradation. The methods tested were expert opinion for identification of potential drivers of land degradation and remote sensing application to determine the extent and rate of land degradation.

STUDY AREA

The proposed national framework for land degradation assessment was tested in Somalia. The Country is in the Greater Horn of Africa and lies between the latitudes of 1° 27′12″S and 11°39′12″N and between the longitudes of 40°38′48″ and 51°16′24″ E. The Country covers 636 240 km^2 (Figure 1). It is a typical dryland country with

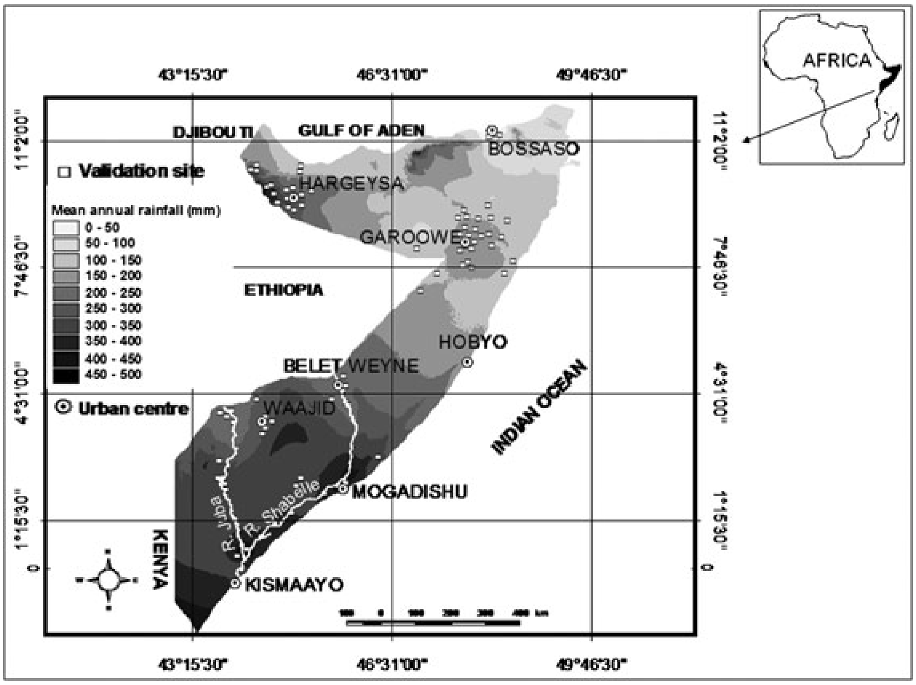


Figure 1. Study area.

low mean annual rainfall (about 282 mm) and arid-land types of soil (e.g. Gypsisols, Calcisols, Arenosols and Leptosols) (WRB, 2006; Omuto *et al*., 2009). Its vegetation is dominated by many species of grass, forbs and *Acacia* and *Commiphora* spp. in areas where the mean annual rainfall is less than 300 mm. Broadleaved deciduous trees dominate areas where the mean annual rainfall is greater than 300 mm (Figure 1).

In terms of land degradation, the country has experienced varying trends of degradation during the past few decades because of several factors. Inappropriate policies and their implementation are examples of such factors. Between 1890 and 1960, the colonial governments in Somalia introduced legislation that marked some parts of northwest Somalia for crop cultivation. The colonial governments later altered the land ownership rights in these areas from communal to individual ownership (Samatar, 1989). Although the legislation was meant to boost food production, it later triggered land degradation in the area, because it was not supported with the requisite agricultural extension services. After the colonial governments, the successive governments did not properly enforce the legislation. This lack of enforcement encouraged neighbouring communities to start crop production gradually. By the mid-1980s, evidence of land degradation (e.g. loss of vegetation and topsoil loss) started emerging because of poor cropland management and agricultural extensification (Samatar, 1989; Omuto and Vargas, 2009).

The charcoal trade is another factor that has contributed to land degradation in Somalia, and it is one of the country's traditional economic activities (Samatar, 1989; Oduori *et al*., 2007). Before 1990, charcoal trade was regulated by the central government through acts of parliament and through co-operative societies. However, these controls ended with the collapse of the central government in the early 1990s. Presently, many tree species have been lost because of the charcoal trade (Oduori *et al*., 2007).

Socio-political upheaval is another driver of land degradation in Somalia. It has caused instability in the central government and a subsequent loss of focus in policy formulation and implementation with regard to land degradation. In addition, it has contributed to the destruction of previously built soil and water conservation structures. The damaged structures were physically destroyed by either war or abandonment. Consequently, they no longer control land degradation and can contribute to downstream gully erosion in some locations (Omuto *et al*., 2009).

MATERIALS AND METHODS

Data

Data sources

The data used in this study consisted of time-series Advanced Very High Rediometric resolution (AVHRR) normalized difference vegetation index (NDVI) images, time-series rainfall amounts, maps of land cover and land use systems (LUS), a digital elevation model (DEM), expert opinion on land degradation and field observations of land degradation features.

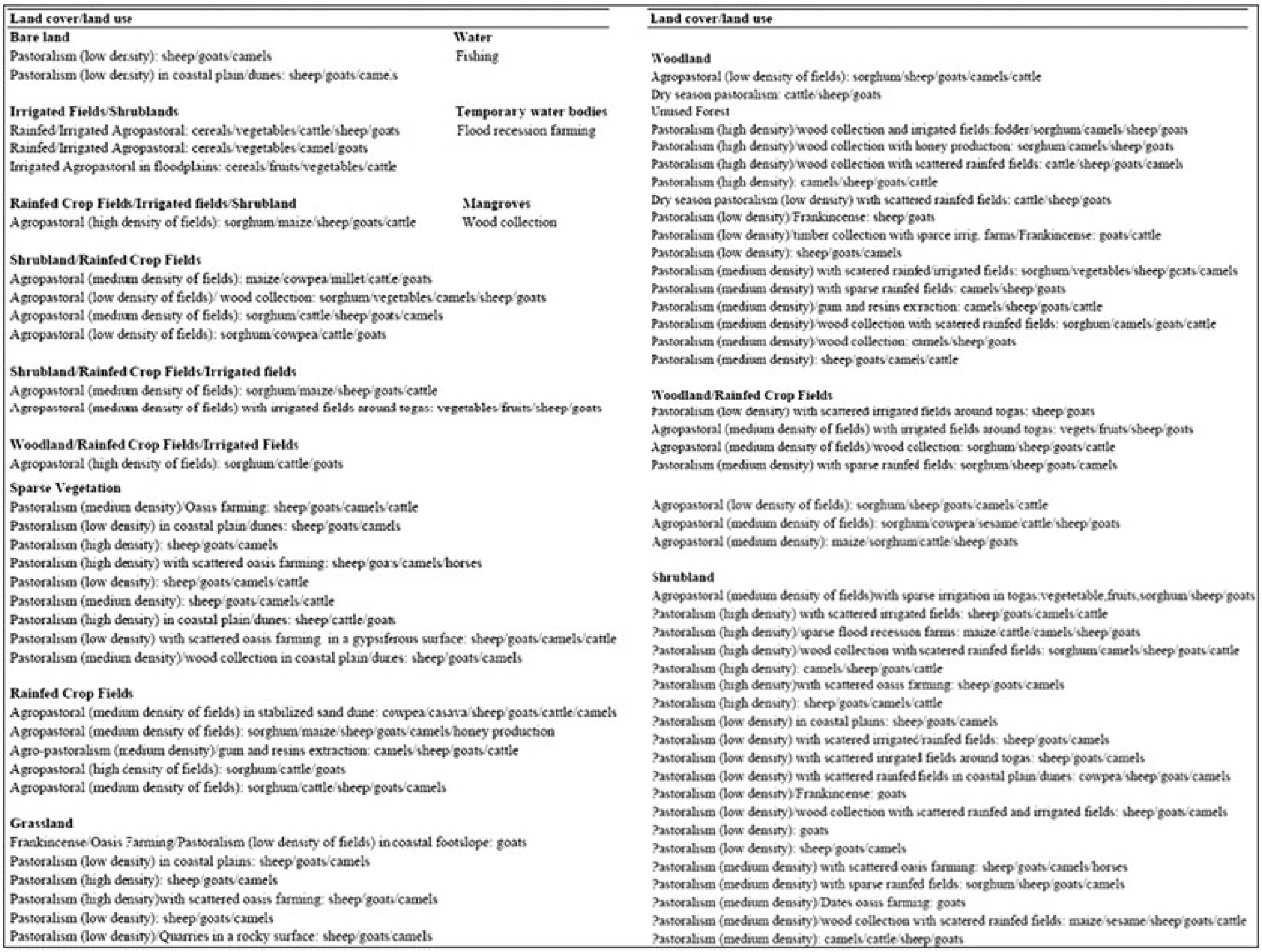
NDVI is a remote sensing index of green vegetation biomass. The time-series data used in this study was comprised of 10-day composite maximum AVHRR NDVI images from January 1982 to December 2009. The images had a spatial resolution of 8 km and were downloaded from http://earlywarning.usgs.gov/adds/datatheme.php on 8 March 2010. The time-series rainfall data were obtained from FAO-SWALIM (www.faoswalim.org). These data consisted of monthly rainfall amounts from January 1982 to December 1990 and from January 2003 to December 2009 for 52 weather stations in the Country. The gap between 1991 and 2002 was caused by the socio-political upheaval in the Country during this period (Muchiri, 2007).

The land cover map was a map of dominant vegetation types in the Country. It was obtained from AFRICOVER (www.africover.org, accessed on 12 March 2009) and contained 39 vegetation types mapped at the scale of 1:200 000. The map was the only available comprehensive and high-resolution land cover map for the Country at the time of this study. In addition, the majority of its land cover classes compared well with the available georeferenced photographs taken by AFRICOVER (www.africover.org) in 1997 and by FAO-SWALIM (Oduori *et al*., 2007) in 2006. LUS map was an integral map of land cover and land use characteristics in Somalia (Nachtergaele and Petri, 2008; Omuto *et al*., 2009). The map was downloaded from www.faoswalim.org on 7 February 2010. It contained 70 units of the land use systems in the Country (Table I). The LUS units were used to incorporate the land use and land cover characteristics, which are the major input factors affecting land degradation in Somalia. They were also the smallest homogeneous areas for collecting expert opinion on land degradation.

The DEM is an elevation image of Somalia. It has a pixel resolution of 90 m and was downloaded from http://srtm.usgs.gov on 15 August 2008. The expert opinions on land degradation were collected from 52 Somali land-resource experts with local knowledge of Somalia's natural resources dynamics. Five experts were from the Ministry of Livestock, Agriculture and Environment in the Transitional Federal Government of Somalia and three from Somaliland. Twenty-five experts were from local non-governmental organizations (NGO), 14 from international NGOs in Somalia and eight were local land users. Altogether, they provided information about the prevalent types and driving forces of land degradation in each LUS unit. They were aided by simple entry forms like those shown in Table II.

To facilitate efficient gathering of the expert opinions on land degradation, the country was divided into three regions: northwest, northeast, and central and southern Somalia. Northwest region (covering about 150 000 km^2) had 14 experts, northeast (covering about 100 000 km^2) had 11,

Table I. Description of units in the land use systems map for Somalia



Land cover/land use	
Bare land	**Water**
Pastoralism (low density): sheep/goats/camels	Fishing
Pastoralism (low density) in coastal plain/dunes: sheep/goats/camels	
Irrigated Fields/Shrublands	**Temporary water bodies**
Rainfed/Irrigated Agropastoral: cereals/vegetables/cattle/sheep/goats	Flood recession farming
Rainfed/Irrigated Agropastoral: cereals/vegetables/camel/goats	
Irrigated Agropastoral in floodplains: cereals/fruits/vegetables/cattle	
Rainfed Crop Fields/Irrigated fields/Shrubland	**Mangroves**
Agropastoral (high density of fields): sorghum/maize/sheep/goats/cattle	Wood collection
Shrubland/Rainfed Crop Fields	
Agropastoral (medium density of fields): maize/cowpea/millet/cattle/goats	
Agropastoral (low density of fields)/ wood collection: sorghum/vegetables/camels/sheep/goats	
Agropastoral (medium density of fields): sorghum/cattle/sheep/goats/camels	
Agropastoral (low density of fields): sorghum/cowpea/cattle/goats	
Shrubland/Rainfed Crop Fields/Irrigated fields	
Agropastoral (medium density of fields): sorghum/maize/sheep/goats/cattle	
Agropastoral (medium density of fields) with irrigated fields around togas: vegetables/fruits/sheep/goats	
Woodland/Rainfed Crop Fields/Irrigated Fields	
Agropastoral (high density of fields): sorghum/cattle/goats	
Sparse Vegetation	
Pastoralism (medium density)/Oasis farming: sheep/goats/camels/cattle	
Pastoralism (low density) in coastal plain/dunes: sheep/goats/camels	
Pastoralism (high density): sheep/goats/camels	
Pastoralism (high density) with scattered oasis farming: sheep/goats/camels/horses	
Pastoralism (low density): sheep/goats/camels/cattle	
Pastoralism (medium density): sheep/goats/camels/cattle	
Pastoralism (high density) in coastal plain/dunes: sheep/cattle/goats	
Pastoralism (low density) with scattered oasis farming in a gypsiferous surface: sheep/goats/camels/cattle	
Pastoralism (medium density)/wood collection in coastal plain/dunes: sheep/goats/camels	
Rainfed Crop Fields	
Agropastoral (medium density of fields) in stabilized sand dune: cowpea/casava/sheep/goats/cattle/camels	
Agropastoral (medium density of fields): sorghum/maize/sheep/goats/camels/honey production	
Agro-pastoralism (medium density)/gum and resins extraction: camels/sheep/goats/cattle	
Agropastoral (high density of fields): sorghum/cattle/goats	
Agropastoral (medium density of fields): sorghum/cattle/sheep/goats/camels	
Grassland	
Frankincense/Oasis Farming/Pastoralism (low density of fields) in coastal footslope: goats	
Pastoralism (low density) in coastal plains: sheep/goats/camels	
Pastoralism (high density): sheep/goats/camels	
Pastoralism (high density)with scattered oasis farming: sheep/goats/camels	
Pastoralism (low density): sheep/goats/camels	
Pastoralism (low density)/Quarries in a rocky surface: sheep/goats/camels	

Land cover/land use
Woodland
Agropastoral (low density of fields): sorghum/sheep/goats/camels/cattle
Dry season pastoralism: cattle/sheep/goats
Unused Forest
Pastoralism (high density)/wood collection and irrigated fields:fodder/sorghum/camels/sheep/goats
Pastoralism (high density)/wood collection with honey production: sorghum/camels/sheep/goats
Pastoralism (high density)/wood collection with scattered rainfed fields: cattle/sheep/goats/camels
Pastoralism (high density): camels/sheep/goats/cattle
Dry season pastoralism (low density) with scattered rainfed fields: cattle/sheep/goats
Pastoralism (low density)/Frankincense: sheep/goats
Pastoralism (low density)/timber collection with sparce irrig. farms/Frankincense: goats/cattle
Pastoralism (low density): sheep/goats/camels
Pastoralism (medium density) with scatered rainfed/irrigated fields: sorghum/vegetables/sheep/goats/camels
Pastoralism (medium density) with sparse rainfed fields: camels/sheep/goats
Pastoralism (medium density)/gum and resins exraction: camels/sheep/goats/cattle
Pastoralism (medium density)/wood collection with scatered rainfed fields: sorghum/camels/goats/cattle
Pastoralism (medium density)/wood collection: camels/sheep/goats
Pastoralism (medium density): sheep/goats/camels/cattle
Woodland/Rainfed Crop Fields
Pastoralism (low density) with scattered irrigated fields around togas: sheep/goats
Agropastoral (medium density of fields) with irrigated fields around togas: vegets/fruits/sheep/goats
Agropastoral (medium density of fields)/wood collection: sorghum/sheep/goats/cattle
Pastoralism (medium density) with sparse rainfed fields: sorghum/sheep/goats/camels
Agropastoral (low density of fields): sorghum/sheep/goats/camels/cattle
Agropastoral (medium density of fields): sorghm/cowpea/sesame/cattle/sheep/goats
Agropastoral (medium density): maize/sorghum/cattle/sheep/goats
Shrubland
Agropastoral (medium density of fields)with sparse irrigation in togas:vegetetable,fruits,sorghum/sheep/goats
Pastoralism (high density) with scattered irrigated fields: sheep/goats/camels/cattle
Pastoralism (high density)/sparse flood recession farms: maize/cattle/camels/sheep/goats
Pastoralism (high density)/wood collection with scatered rainfed fields: sorghum/camels/sheep/goats/cattle
Pastoralism (high density): camels/sheep/goats/cattle
Pastoralism (high density)with scattered oasis farming: sheep/goats/camels
Pastoralism (high density): sheep/goats/camels/cattle
Pastoralism (low density) in coastal plains: sheep/goats/camels
Pastoralism (low density) with scatered irrigated/rainfed fields: sheep/goats/camels
Pastoralism (low density) with scattered irrigated fields around togas: sheep/goats/camels
Pastoralism (low density) with scattered rainfed fields in coastal plain/dunes: cowpea/sheep/goats/camels
Pastoralism (low density)/Frankincense: goats
Pastoralism (low density)/wood collection with scattered rainfed and irrigated fields: sheep/goats/camels
Pastoralism (low density): goats
Pastoralism (low density): sheep/goats/camels
Pastoralism (medium density) with scattered oasis farming: sheep/goats/camels/horses
Pastoralism (medium density) with sparse rainfed fields: sorghum/sheep/goats/camels
Pastoralism (medium density)/Dates oasis farming: goats
Pastoralism (medium density)/wood collection with scatered rainfed fields: maize/sesame/sheep/goats/cattle
Pastoralism (medium density): camels/cattle/sheep/goats

and central and south (covering 386 240 km^2) had 27 experts. Participatory workshops were organized for the experts in each region to support and coordinate their assessment of land degradation. There were three workshops for each region. In the first workshop, a participatory discussion on land degradation was organized, and the objectives of the land degradation assessment exercise were elaborated. In the second workshop, the experts were appraised on how to use interactive Geographic Information System (GIS) maps of the land use systems and the data collection forms (Table II). Terms, such as 'driving forces' and 'types of land degradation,' were also explained using the illustrations and examples from Somalia. In the last workshop, the experts used information obtained from the previous two workshops to assess land degradation in their region. They were aided with a printed LUS map and data collection forms (Table II). The map was drawn to scale and contained landmark features (e.g. roads, hills/valleys, urban centres, schools and mosques) to help the experts identify different locations in their regions. At the end of the workshops, the collected data were converted into a digital database of expert opinion on land degradation in Somalia.

In addition to the time-series data and expert opinion, field observations were also conducted in randomly selected sites during 2007. These sites consisted of 82 randomly selected locations in the three regions of the country (25 locations in the northeast, 46 in the northwest and 11 in the south) (Figure 1). Each location had two replicate point-observations 100 m apart along the longitude. The validation exercise entailed observations of land degradation evidence and discussions with the local land users (within a radius of 100 m) regarding the degradation's trends. All field sites were georeferenced using handheld Geographic Positioning System (GPS) receivers and visually observed for evidence of land degradation. The guidelines for observing land degradation evidence were the following: (i) evidence of

Table II. Example of a completed form for expert assessment of land degradation

LUS unit	Land degradation types	Causes of land degradation: Indirect[a]	Causes of land degradation: Direct[b]
1	Soil erosion by water	War	Reduction of cover
	Loss of vegetation cover	Population pressure	Excessive tree harvesting
19	Salinization	Communal land tenure system	Excessive irrigation
	Loss of soil fertility	Lack of agronomy skills	Spread of weeds
	Riverbank erosion	Lack of law enforcement	Lack of erosion control measures
25	Loss of vegetation cover	Lack of law enforcement	Excessive fuelwood gathering
	Topsoil loss by runoff	Communal land tenure system	Lack of erosion control measure
30	Loss of vegetation cover	Communal land tenure system	Overgrazing/forest fires
	Loss of vegetation species	Poverty	Excessive tree harvesting
	Surface sealing and crusting	Lack of agronomy skills	Cultivation of unsuitable soil
35	Topsoil loss by wind	Lack of ground cover	High wind speeds

[a]Conditioning factors contributing to pressure on the land resources;
[b]Direct forces driving the degradation.

vegetation loss (e.g. evidence of charcoal production, tree-stumps or cut-branches and signs of overgrazing); (ii) evidence of vegetation species change (e.g. suggestions from land users about invasive species, land use changes and encroachment of croplands); (iii) evidence of soil physical degradation (e.g. presence of gullies, rills, and sheet erosion, dust storms, surface sealing and plough pans); (iv) and evidence of soil chemical degradation (e.g. history of nutrient decline and presence of salt deposits on the soil surface). The discussions with local land users targeted the history of land degradation during the 5 years preceding 2007. The land users also gave their opinion on the trends and possible causes of land degradation on their parcels of land.

Data preparation

The time-series remote sensing images were already georeferenced and pre-processed for a maximum 10-day composite NDVI (Tucker *et al.*, 2005). Therefore, data preparation was limited to minor adjustments to convert the image's digital numbers into NDVI indices, as recommended in the accompanying metafiles. The time-series rainfall data had gaps between January 1991 and December 2002. No attempt was made to fill this gap, and the corresponding NDVI data for this period was removed from the subsequent analysis to maintain consistency with the rainfall data.

The point-data monthly rainfall amounts were extrapolated to produce spatial images of monthly rainfall amounts. This was performed to maintain a uniform data format for all the datasets and to aid pixel-level assessment of land degradation. The extrapolation involved predicting the rainfall amounts in un-gauged locations using data from the weather stations and using predictors such as elevation (from DEM), *x* and *y* coordinates, and distance from the shoreline. These predictors were chosen because they had a significant correlation with rainfall in Somalia (Omuto and Vargas, 2009; Omuto *et al.*, 2009). The multiple linear regression kriging method given in Equation (1) was used to accomplish the extrapolation (Hengl *et al.*, 2007).

$$\hat{z}(x,y) = \sum_{k=0}^{p} \hat{\beta}_k * q_k(x,y) + \sum_{i=1}^{n} \lambda_i * e_i(x,y) \qquad (1)$$

Where: $\hat{z}$ is the predicted rainfall amount at location (*x,y*), $\hat{\beta}$ is the multiple regression coefficient, λ is the kriging weight, q_k are the predictors (e.g. DEM, *x* and *y* coordinates and distance to the shoreline) at location (*x,y*), *e* is the interpolation residual, *p* is the number of pixels in the input images, and *x* and *y* are the geographic coordinates. Equation (1) was implemented using R Computing Software (R Development Core Team, 2010). A holdout cross-validation was first performed to check the prediction accuracy for each month's rainfall data. Then, the entire measured monthly rainfall data were used to produce the image of rainfall amount for that month. The cross-validation tests involved using two-thirds of each month's rainfall amount for spatial prediction and testing the output on the remaining one-third. Validation results showed that the correlation between the actual and predicted monthly rainfall datasets was between 55 per cent and 91 per cent. In addition, the predicted rainfall amounts were also within one standard deviation of the long-term averages of the measured values. Therefore, these data were considered to be adequate inputs for assessing land degradation. The final rainfall maps were then re-sampled to 8-km pixel resolution to correspond with the resolution of the NDVI images.

The expert opinions on land degradation were also converted into a spatial data format for compatibility with the rainfall and NDVI images. The conversion involved linking the LUS units in the database of expert opinion to those in the LUS map. The linkage was done via the GIS database link-functions in the ArcGIS® software (ESRI, 2005). The experts' opinion was then transferred into the LUS map after linking the two databases.

Data Analysis

Remote sensing analysis of human-induced dynamics of vegetation cover

Vegetation is an important source of livelihood for the pastoral communities living in Somalia. These communities use it as a source of income from the charcoal trade and from sale of frankincense. They also use it as pasture for their livestock. Besides direct service to the people, vegetation also protects water catchment areas and prevents soil erosion. Its loss is therefore an important type of land degradation in the Country. In fact, some studies have suggested that loss of vegetation in Somalia is a trigger for other types of land degradation (e.g. soil erosion, loss of habitat and decline of soil moisture) (Samatar, 1989; Alim, 1997; Omuto and Vargas, 2009). This study used the dynamics of vegetation cover to index the rate and extent of land degradation in Somalia.

Vegetation cover dynamics were determined using the residual trend method developed by Wessels *et al*. (2007). In this method, the NDVI-rainfall relationship is first modelled, and the resultant residuals are then extracted. The residuals are the differences between the remotely sensed and the predicted NDVI. The modelling process and the extraction of the residuals are then repeated for given time periods to produce time-series residuals. Loss of vegetation cover is inferred if the trend of the time-series residuals has a negative slope. An increase of vegetation cover is inferred if the trend has a positive slope (Evans and Geerken, 2004). This approach has been used in many places in the drylands. Evans and Geerken (2004) first used the approach in the Middle East to discriminate climate from human-induced land degradation. Then Wessels *et al*. (2007) tested it in South Africa and Bai *et al*. (2008) used it for global assessment. They all show its potential in identifying land degradation characteristics associated with loss of vegetation cover. Omuto *et al*. (2010) reviewed the application of this method and potential opportunities for its improvements. In this study, modelling of the NDVI-rainfall relationship was accomplished using the mixed-effects technique. The mixed-effects technique is a unique regression analysis that simultaneously models landscape-level environmental relationships and the same relationship for different groups in the landscape (Pinheiro and Bates, 2000). It was used to model the NDVI-rainfall relationship for Somalia and for different vegetation types in the country. By including vegetation types in the modelling, the mixed-effects technique accounted for possible variations in the vegetation's responses to rainfall. These variations have been recognized by many authors but have not been adequately included in modelling the NDVI-rainfall relationship (Nicholson and Farrar, 1994; du Plessis, 1999, Williams and Albertson, 2006). In addition to accounting for vegetation effects in

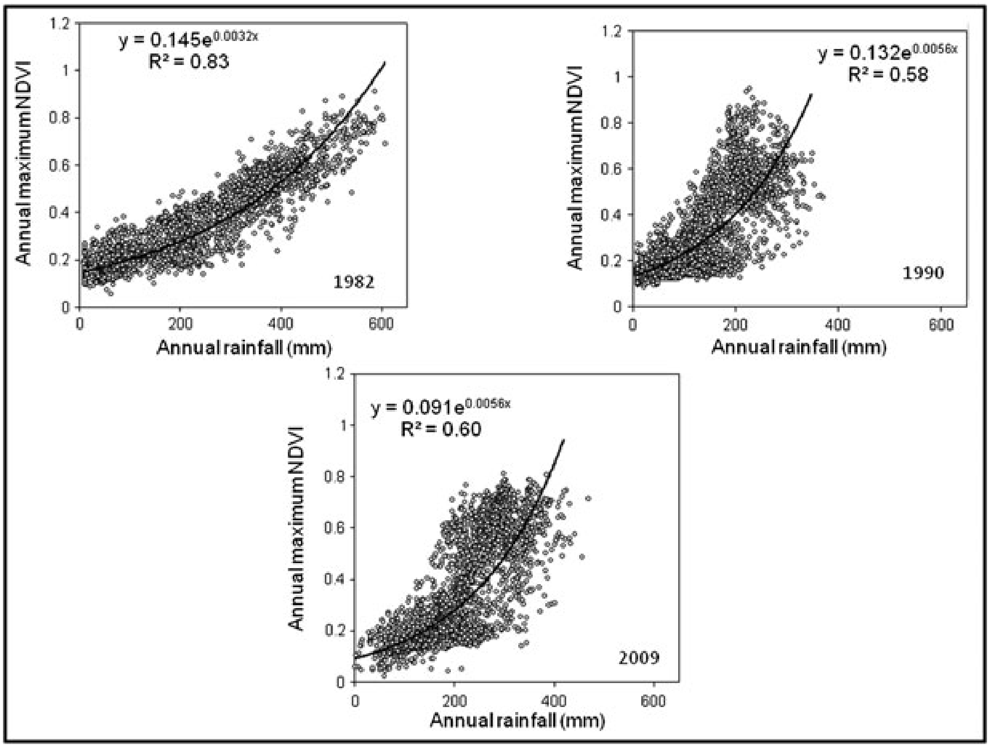


Figure 2. Relationship between normalized difference vegetation index and rainfall amounts in Somalia.

the NDVI-rainfall relationship, the mixed-effects technique can also produce unbiased estimates of the time-series residuals that are necessary for accurate assessment of changes in vegetation cover (Omuto *et al*., 2010). An exponential mixed-effects model was used for the NDVI-rainfall relationship in Somalia. The exponential model was used because NDVI seemed to have an exponential relationship with rainfall amounts in the country (Figure 2). This relationship resembled what Hein and de Rider (2006) also obtained for the Sahelian conditions. The exponential model used in this study is given in Equation (2).

$$\begin{aligned} NDVI_{ij} = {} & (B_1 + b_{1i}) * \exp\left[(B_2 + b_{2i}) * Rain_j\right] \\ & + \varepsilon_{ij}, \quad i \\ = {} & 1, 2, 3, \ldots., 39 \end{aligned} \qquad (2)$$

Where: *NDVI* and *Rain* are the input NDVI and rainfall data, ϵ is the modelling residual, *B* is the fixed-effect (which represents the average modelling parameter for the whole country), *b* is the random-effect (which represents the modelling parameter for dominant vegetation types in the country), *i* is the number of vegetation types in the land cover map ($i = 39$), and *j* is the number of pixels in the input NDVI and rainfall images ($j = 10180$). Equation (2) was also evaluated using the R Computing Software (R Development Core Team, 2010).

The inputs for modelling Equation (2) were the land cover map and images of 6-month time-series maximum NDVI and rainfall amounts. The 6-month data were used to accommodate the bimodal pattern of the rainfall characteristics and NDVI peaking times in Somalia (Figure 3). The modelling process was repeated in groups of 6 months: from January to June and from July to December. This was done from January 1982 to December 1990 and from January 2003 to December 2009.

After modelling the NDVI-rainfall relationship, the resultant residuals for each pixel were extracted. The residuals were first analyzed for the presence of serial autocorrelation using an empirical autocorrelation function at the 95 per cent confidence interval (Pinheiro and Bates, 2000). Any available autocorrelation was removed using an autoregressive moving average. The final time-series residuals were then used to index land degradation in the country. The gradient (or slope) of the residuals' trend with time for each pixel was used for the indexing, as shown in Equations (3) and (4).

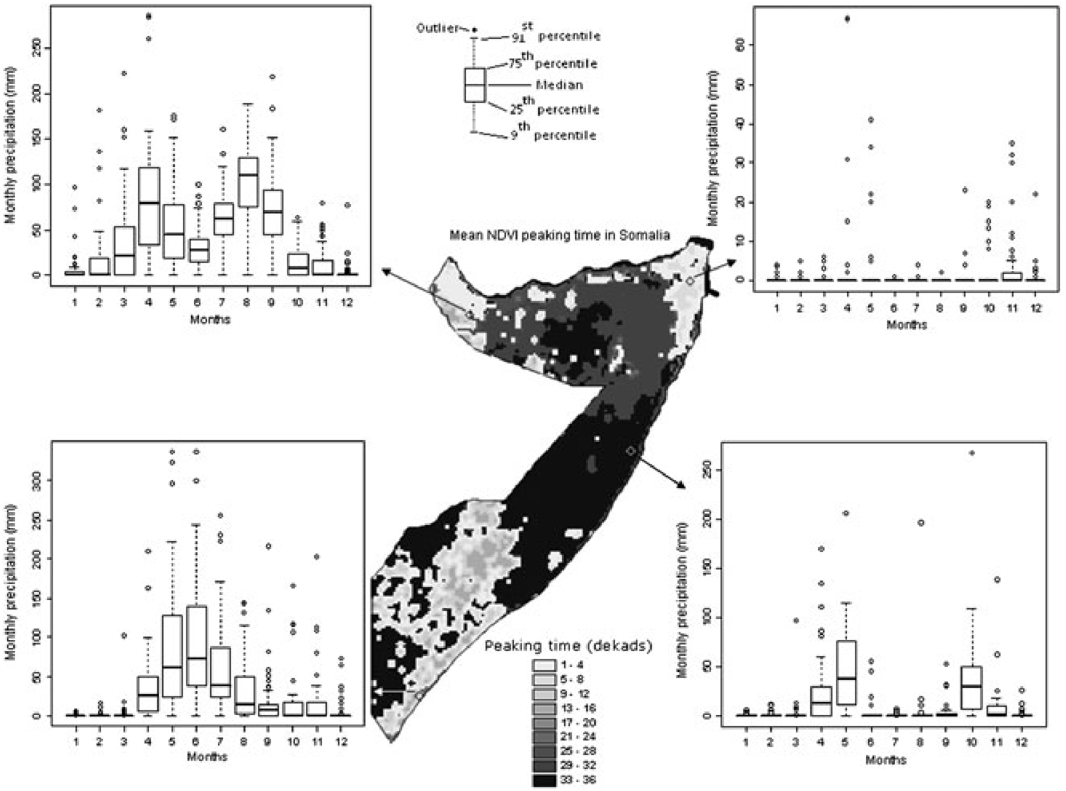


Figure 3. Mean monthly rainfall distribution and normalized difference vegetation index peaking times in Somalia between 1982 and 1990 and between 2003 and 2009.

For negative trend:

$$\begin{array}{ll} & \underline{\text{Negative slopes}} \qquad\qquad\qquad\qquad \underline{\text{Rate}} \\ \begin{array}{l} Degradation \\ status \end{array} = & \left\{ \begin{array}{ll} slope \geq -60\,\text{per cent}, & \text{Extreme} \\ -60\,\text{per cent} \leq slope \leq -30\,\text{per cent} & \text{Strong} \\ -30\,\text{per cent} \leq slope \leq -15\,\text{per cent} & \text{Moderate} \\ -15\,\text{per cent} \leq slope \leq -1\,\text{per cent} & \text{Light} \end{array} \right. \end{array} \tag{3}$$

For positive trend:

$$\begin{array}{ll} & \underline{\text{Positive slopes}} \qquad\qquad\qquad\qquad \underline{\text{Rate}} \\ Non - degraded = & \left\{ \begin{array}{ll} slope \geq 60\,\text{per cent} & \text{Strong improvement} \\ 60\,\text{per cent} \leq slope \leq 30\,\text{per cent} & \text{Moderate improvement} \\ 30\,\text{per cent} \leq slope \leq 15\,\text{per cent} & \text{Light improvement} \\ 15\,\text{per cent} \leq slope \leq -1\,\text{per cent} & \text{Invariant} \end{array} \right. \end{array} \tag{4}$$

Where: *slope* is the gradient of the residuals' trend. The classes under *Rate* in Equations (3) and (4) were chosen for convenience to categorize land degradation and improvement in the country. The areas covered by the above degradation rates defined the extent of land degradation in Somalia.

Expert assessment of land degradation

The expert opinions contained in the LUS database were used to produce maps of prevalent types and causes of land degradation in Somalia. The degradation causes were divided into direct and indirect drivers. Direct drivers of land degradation were human activities that accelerated the degradation of land resources with which they were in direct contact (e.g. down-slope tillage practices, overgrazing, tree cutting). Indirect drivers of land degradation were conditioning factors that favoured the direct drivers of degradation (e.g. land tenure policy, war and conflict).

National assessment of land degradation

Remote sensing analysis of vegetation dynamics, expert opinion and field validation processes were used to conceptualize the national land degradation assessment framework. The framework had four major steps (Figure 4): spatial prediction of weather station rainfall data, remote sensing analysis, expert opinion on prevalent types and causes of land degradation and field validation. These steps were integrated to produce a map and database of the causes, rate and extent of national land degradation. The evidence of degradation obtained from field observations was used to validate the outputs from the remote sensing analysis and expert opinion.

RESULTS AND DISCUSSIONS

Remote Sensing Analysis of Land Degradation in Somalia

Residuals obtained from modelling of the NDVI-rainfall relationships were generally positive in the early-1980s and negative in the late-2000s. Their spatial distribution also showed that there were some locations that exhibited a gradual expansion of the areal extent of negative residuals from a few pixels in 1990 to a cluster of negative pixels in 2009. Example areas were located east of Hargeysa, around Galckayo, and around Garoowe (Figure 5).

Because the residuals were the differences between remotely sensed and predicted NDVI data, their negative values meant that the predicted NDVI data were greater than the corresponding NDVI data from the remote sensing images. Theoretically, negative residuals were possible when above-average rainfall amounts were used in modelling of the NDVI-rainfall relationship or when the actual vegetation cover produced low NDVI data in the remote sensing images. Similarly, positive residuals were possible when below-average rainfall was used in modelling of the NDVI-rainfall relationship or when there was adequate vegetation cover to give high values in the NDVI images. Time-

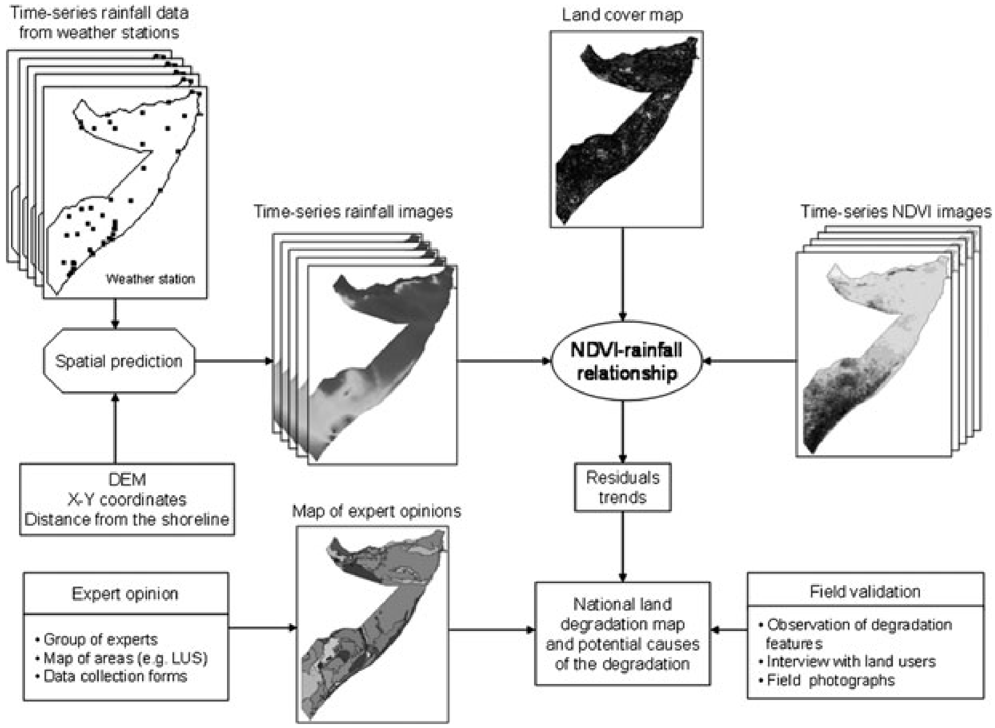


Figure 4. Conceptual framework for national land degradation assessment.

series rainfall anomalies were used to determine whether above-average or below-average input rainfall amounts produced the negative or positive residuals. Rainfall anomalies are dimensionless quantities used for comparing rainfall amounts on a given date to the long-term rainfall amount (Nikken, 1999). They were obtained as the standard deviation of scaled differences between rainfall in a given year and the long-term average rainfall amount. These data

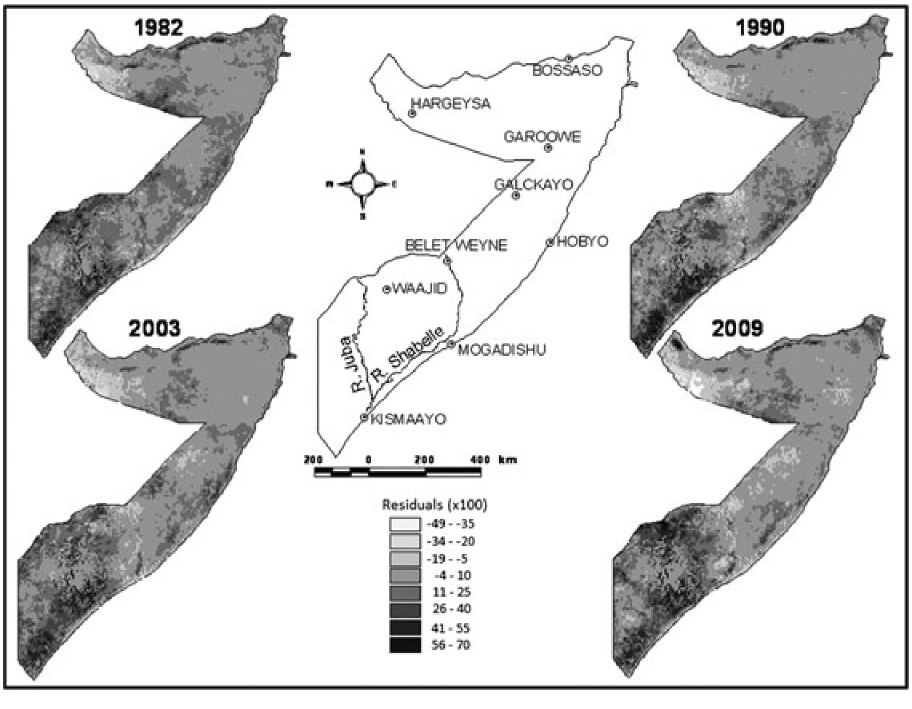


Figure 5. Normalized difference vegetation index-rainfall model residuals for Somalia.

indicated that the annual rainfall in Somalia was below average in 1990, 2003 and 2009. These amounts could not have caused the negative or positive residuals during these times. Therefore, the sign of the resultant residuals from modelling of the NDVI-rainfall relationship was an indication of low or high vegetation cover.

Time-series trends of the residuals in central Somalia, along the coast of Indian Ocean, and in northwest Somalia were generally declining between 1982 and 2009. The declining trend indicated that the residuals became more negative with time, thus suggesting a loss of vegetation cover with time and a possible presence of land degradation in Somalia. Areas with steep declining trends (where the slope of the residuals' trend $\geq$ 30 per cent) were classified as having a strong rate of land degradation. Those with gently declining trends (with slopes $\leq$ 15 per cent) were classified as having a light rate of land degradation. Strong rates of land degradation were found along the coast of the Indian Ocean, around Garoowe in the northeast, and near the north-western border with Ethiopia (Figure 6). Central and northern Somalia had moderate to light rates of degradation. There were also areas that had increasing trends in the time-series residuals between 1982 and 2009. These areas included the upper parts of the south, some areas in the north, and areas along the north western coast of the Gulf of Aden (Figure 6). Their increasing residuals' trend was used to infer improving land conditions in Somalia during this period.

In terms of the extent of land degradation in Somalia, the remote sensing analysis classified about one-third (~31 per cent) of the country as degraded and 17 per cent as exhibiting evidence of land condition improvements (Table III). The majority of degraded areas were moderately degraded, implying that land degradation in the Country may still be controllable. However, the control should be urgently implemented because the rate of degradation is greater than the rate of land improvement.

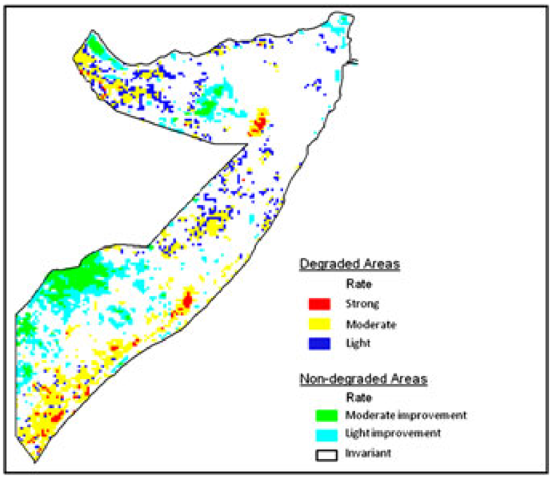


Figure 6. Extent and rate of land degradation in Somalia based on remote sensing analysis. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Table III. Extent and rate of land degradation in Somalia between 1982 and 2009

Land condition	Rate	Extent	
Degraded areas		Area (km^2)	Per cent
	Strong	12 672	2·0
	Moderate	118 848	18·7
	Light	62 976	9·9
	Total	194 496	30·6
Improvements			
	Moderate	34 688	5·5
	Light	70 528	11·1
	Total	105 216	16·6
Non-degraded	Invariant	336 512	52·8
	Total	336 512	52·8

Prevalent Types of Land Degradation in Somalia

The experts identified loss of vegetation cover as the most prevalent type of land degradation in Somalia (Figure 7). The three separate groups of experts assessing different parts of the country independently agreed that it was the major national degradation problem. Their assessment showed that about half of the country (~53 per cent) had suffered loss of vegetation cover. The experts also identified loss of topsoil by runoff and decline of average soil moisture as the other dominant types of land degradation in the country. Topsoil loss was prevalent in about 13 per cent of the

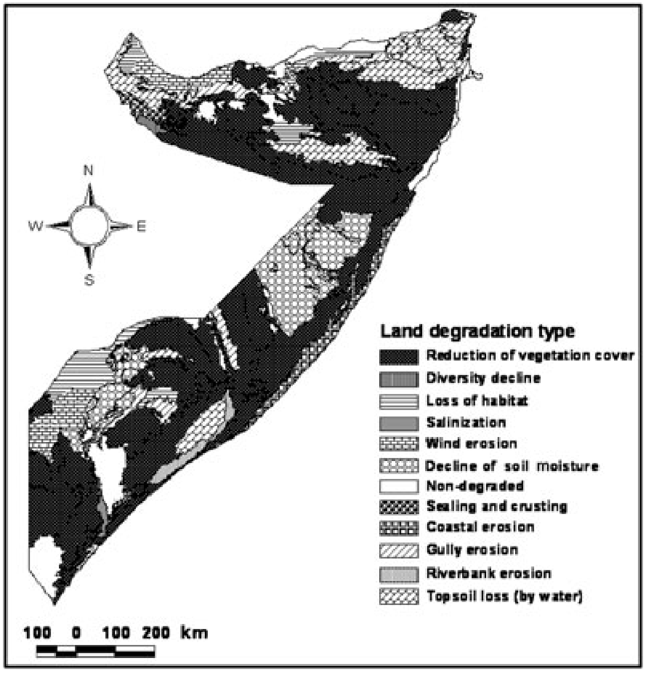


Figure 7. Prevalent types of land degradation in Somalia based on experts opinion.

country, and decline in soil moisture was prevalent in about 12 per cent of Somalia. Topsoil loss was observed mainly in the north and in the south along the lower parts of Shabelle River. The decline of soil moisture was cited around Galckayo in the centre and around Waajid in the south (Figure 7). Other observed land degradation types were river-bank erosion along the Shabelle River, salinization in the floodplain of the Juba River, soil surface sealing and crusting in the plateau west of Hargeysa, and coastal erosion along the coast of the Indian Ocean. There were also minor problems of biodiversity decline in north western Somalia.

The dominance of loss of vegetation cover among the prevalent types of land degradation justified the application of remote sensing in land degradation assessment, which was based on the vegetation cover dynamics. Generally, vegetation protects other land resources from agents of degradation and, therefore, its loss can potentially precipitate the onset of other types of land degradation such as soil loss, decline of soil moisture and the like (Symeonakis and Drake, 2004). This linkage was evident in the correlation between the results from the experts' assessment and remote sensing evidence of land degradation. For example, the areas the experts identified as exhibiting topsoil loss (Figure 7) were also identified by remote sensing analysis as having a strong rate of land degradation (Figure 6). Loss of vegetation cover, as identified by remote sensing, was an indicator that the cover that protected soil against erosion had been removed. Once the cover was removed, the soil underneath became vulnerable and subsequently showed signs of topsoil loss, as observed by the experts. For this case, the loss of vegetation behaved as the primary land degradation problem, which led to topsoil loss as the secondary degradation problem. In central Somalia, the experts suggested decline of soil moisture as the dominant type of land degradation. These results were supported by the outputs from remote sensing analysis, which also identified the area with a light rate of land degradation.

In some areas, the land degradation assessment results from the remote sensing analysis seemed to contradict the experts' opinion. Example areas where the data seemed contradictory included around Waajid in the south, near the north western border with Djibouti and in central Somalia. The remote sensing analysis portrayed these areas with a light rate of improvement in land conditions, but the experts had indicated loss of habitat and decline of soil moisture. Further investigations were performed to determine the reasons for these contradictions. The investigations used the land cover map, the time-series parameters from the NDVI-rainfall modelling, and reports from previous studies. It was found from the land cover map that the areas were classified by AFRICOVER in 1997 as dominated by herbaceous vegetation. Similarly, land cover classification by Alim (1997) and Oduori *et al*. (2007) also put the vegetation in these areas as mainly herbaceous. However, Samatar (1989), who studied the rural transformations in Somalia, classified these areas as being dominated by shrubs during the 1980s. Evidence from these studies suggests a change of vegetation types in these areas from shrubs during the 1980s to herbaceous vegetation after 1990. The statistical characteristics of the NDVI-rainfall modelling parameters for these areas were also compared with other areas with similar vegetation types. Before 1990, the modelling parameters compared well with other areas that were dominated by shrub-types of vegetation. After 1990, the modelling parameters for areas around Waajid and along the Somalia border with Djibouti changed to resemble the parameters for areas under herbaceous vegetation. This change gave the impression of changes of vegetation type. Studies by Omuto *et al*. (2010), which also used NDVI-rainfall modelling parameters to infer possible changes in vegetation composition, supported the deduction of a possible change of vegetation type around 1990. Altogether, this evidence pointed to a possible change of vegetation type from shrubs to herbaceous around 1990. This change could have caused a corresponding increase of the green biomass without necessarily increasing the vegetation cover (Barlow *et al*., 2003). Because the remote sensing analysis used in this study was based on the NDVI characteristics that are only sensitive to changes in the green biomass, it was not uncommon for the analysis to conclude a positive trend (and hence improvement of the land condition) for the areas that had the vegetation change from shrubs to herbs. This error could be a potential limitation of the remote sensing analysis in land degradation assessment.

Drivers of Land Degradation in Somalia

The main causes of land degradation in Somalia were divided into two groups: direct and indirect. Direct causes were defined as human activities directly exerting pressure on the land resources. They included overgrazing, tree cutting (for fuel wood and charcoal production), and poor agronomic practices in the crop production areas (Figure 8). Overgrazing affected almost all parts of the country because it was practised by the pastoral communities that are the dominant clans in Somalia. The pastoralists traditionally keep large herds of livestock and rely on the natural vegetation as pasture for their livestock. Tree cutting was also practised by some communities in north and south Somalia. Members of these communities cut trees to clear land for crop production in high-rainfall areas. They also cut trees to produce charcoal for sale and to use as a dependable source of energy. In north eastern Somalia, the locals also harvest trees for frankincense that is used for local consumption and export. Altogether, the tree cutting activities directly contributed to loss of vegetation because they were performed without tree replanting. Poor agronomic practices

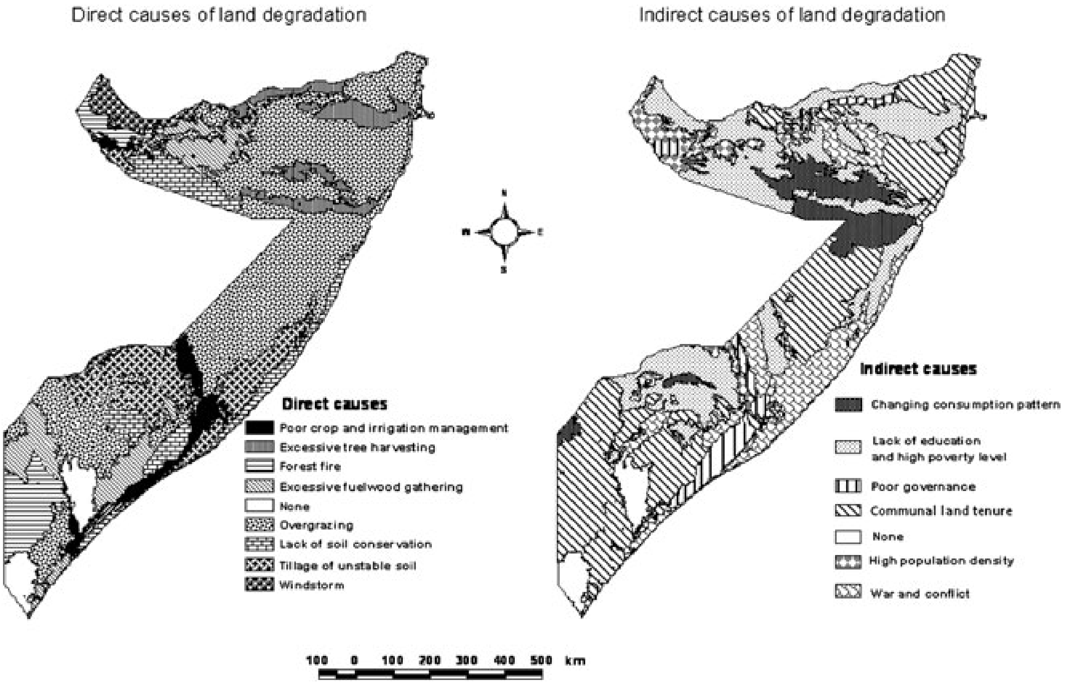


Figure 8. Main drivers of land degradation in Somalia based on experts opinion.

were a major problem in crop production areas such as the north-western plateau and the floodplain between the Juba River and Shabelle. These poor practices included down-slope ploughing with ox-drawn implements, burning of animal manure instead of incorporation into the soil, and lack of soil and water conservation practices. The people burned animal manure because they believed that the manure contained weed seeds and parasitic ticks, which are vectors for animal diseases. They hoped that burning manure would break the life cycle of animal diseases and stubborn weeds, which they believed would outweigh the soil quality benefits that could accrue via incorporation of manure into the soil.

Indirect causes of land degradation were conditioning factors that favoured the direct causes of land degradation. They included land tenure practices, the prevailing illiteracy and poverty level, war and conflict, poor governance and high population density in some areas (Figure 8). The communal land tenure system was dominant in the central, south, and north eastern Somalia. This land tenure system encouraged the keeping of free-range livestock in areas where the movement and grazing of animals was not restricted. Consequently, the practice promoted overgrazing as was cited by the experts as a direct driver of land degradation (Figure 8). Poor crop and irrigation management was another direct cause of land degradation that prevailed under the lack of good governance in areas where irrigation was practised. These drivers of degradation caused salinization, soil erosion, and sealing and crusting in the affected areas (Figure 7). It is also important to note how the lack of education as indirect cause coincided with tillage of unstable soil as a direct cause of land degradation in South Somalia (Figure 8). Lack of education precipitated practices such as down-slope tillage, burning of manure and the like in crop production areas. These practices accelerated topsoil loss, sealing and crusting, soil compaction, and nutrient decline. Along the coast of the Indian Ocean, the prevailing war and conflict destroyed the soil and water conservation structures meant to control tidal erosion and sand-dune movement. The war also interrupted regular maintenance of the conservation structures so that they no longer effectively controlled soil erosion. It was therefore not surprising that lack of properly functioning soil conservation structures was cited as the direct cause of land degradation in this area (Figure 8).

Field Observations of Land Degradation in Somalia

Fifty-one degraded and 31 non-degraded locations were visited during the field validation exercise. Of these sites, 63 per cent of the degraded sites and 81 per cent of non-degraded sites were correctly identified by the remote sensing analysis (Table IV). However, the analysis misclassified 19 degraded areas as non-degraded. Ten of the misclassified areas were located in the northeast, six were in the south, and three were in north western Somalia. In the northeast, people were selectively cutting trees for charcoal production and leaving grass intact. This selective cutting of trees was

Table IV. Confusion matrix for comparing modelled and observed land degradation

		Modelled land degradation			
Observed land degradation		Remote sensing analysis		Experts assessment	
	Total	Degraded	Non-degraded	Degraded	Non-degraded
Degraded	51	32	19	51	0
Non-degraded	31	6	25	31	0
Total	82	38	44	82	34
*Specificity (per cent)		81		0	
Sensitivity (per cent)		63		100	
Misclassification rate (per cent)		30		38	
Overall (per cent)		70		62	

*Specificity is correct identification of non-degraded site while sensitivity is correct identification of degraded sites

not easily detectable at the 8 km pixel resolution of the input NDVI images. In south and western Somalia, the misclassification was due to both a lack of proper identification of new vegetation species and a coarse spatial resolution of the input NDVI images. Some vegetation species had been replaced by new ones, and the data still exhibited a consistent NDVI response to rainfall. Interviews with the local land users and physical observations in the field suggested encroachment of some new species into the traditional vegetation communities. Although the local land users reported this encroachment as land degradation, remote sensing analysis described the area as having undergone improvements in land condition. The remote sensing analysis also misclassified six non-degraded sites as degraded (Table IV). Four of the misclassified sites were croplands at the edges of natural bushlands, and two were in open shrublands on the hillslopes. Again, the misclassification could have been due to the coarse spatial resolution of the NDVI images, which lumped small parcels of croplands together with adjacent natural vegetation.

The experts' assessment of land degradation had a high accuracy in identifying truly degraded areas (100 per cent) compared with a 63 per cent accuracy in the remote sensing analysis (Table IV). This result may have been obtained because the experts were able to identify other degradation types (e.g. salinization, sealing and crusting, and diversity decline) that were not amenable to the remote sensing method. However, the remote sensing method performed better in correct identification of non-degraded sites (81 per cent) than the experts' assessment (0 per cent). The experts' opinion seemed biased towards degraded land. Their opinion described almost every part of the Country as degraded, except for two areas in the south (Figure 7). Although none of the validation sites were located in these two areas (and hence the 0 per cent specificity reported in Table IV), in our opinion, this was an exaggeration of the arid conditions of the land. Evidence from the time-series still-camera photographs taken in some of the arid areas with similar conditions did not show much change of the land characteristics. Therefore, we think that the experts overestimated the severity of land degradation in the arid areas. Otherwise, the results from the two assessment methods were mostly comparable; which suggested that they indeed reflected the actual land degradation status at the national level.

Potential Sources of Error in the Framework

In this study, we established that errors associated with remote sensing application in land degradation assessment were mainly those arising from the use of coarse spatial resolution images to monitor sub-pixel changes of the land conditions and the NDVI limitation in separating change of vegetation cover from the change of green biomass. These shortcomings can potentially lower the overall accuracy of the remote sensing approach in land degradation assessments. In order to overcome them, we recommend use of high-resolution images and concurrent application of ground validation and improved image modelling approaches. For the experts' assessment approach, the main sources of error were over-estimation of the degradation conditions of the arid environments and poor judgement of the degradation conditions in areas where they don't have concrete natural resources information. These limitations can be overcome by expanding the number of experts, increasing the frequency of expert assessment schedules, and standardizing their assessment procedures.

CONCLUSIONS

This study used remote sensing and expert opinion to formulate a national land degradation assessment framework. The framework is rapid enough for large-area assessment and is therefore suitable for application at the national scale. Its application in Somalia shows that it is fairly accurate in identifying degraded areas and that it provides an opportunity for identifying areas to target with comprehensive local assessments. The framework can also identify the rate of land degradation and improvement, which is a necessary step to inform policy decisions on the urgency needed for action in land degradation control. The framework incorporates methods that include participatory contribution of local experts and of local land users' opinion of the degradation's drivers. This involvement is important because the locals are also stakeholders in land degradation control. Overall, the framework can produce over 60 per cent accuracy in land degradation assessment. In addition, its simplicity, use of freely available input data, and self-triangulation of assessment methods makes it suitable for rapid assessment of land degradation at the national scale.

The proposed national land degradation assessment framework was applied in Somalia, where it revealed that about one-third of the country was degraded because of the loss of vegetation cover, topsoil loss and decline of soil moisture. The framework also identified overgrazing, excessive cutting of trees, and poor agronomic practices in agricultural areas as the primary drivers of land degradation in Somalia. These drivers are encouraged by the prevailing communal land tenure practices, poor governance, and civil war in the Country.

ACKNOWLEDGEMENTS

This study was part of the activities performed by Somalia Water and Land Information Management (SWALIM) project. The project is financed by the European Union. The study also received technical support from the United Nations Food and Agriculture Organization (UN-FAO), SWALIM staff members and the Somali land resources experts. Mr. Ali Ismail, Mr. Osman Abdulle, and Prof. Hussein Iman were instrumental in coordinating the field validation and workshops during the experts' assessment of land degradation in Somalia.

REFERENCES

Alim SM. 1997. Inventory Report for Somalia. Technical Report No. GCP/RAF/287/ITA. FAO-AFRICOVER East Africa, FAO.

Bai ZG, Dent DL, Olsson L, Schaepman ME. 2008. Proxy global assessment of land degradation. *Soil Use and Management* **24**: 223–234.

Barlow EL, D'Antonio CM, Swartz H. 2003. Response of herbs to shrubs removal across natural and experimental variation in soil moisture. *Ecological Applications* **13**: 1375–1387.

Diouf A, Lambin EF. 2001. Monitoring land cover changes in semi-arid regions: Remote sensing data and field observations in the Ferlo, Senegal. *Journal of Arid Environments* **48**: 129–148.

Dregne HE. 2002. Land degradation in the drylands. *Arid Land Research & Management* **16**: 99–132.

Eklund P. 1991. Development of policy on land degradation in the Sahel: A reassessment. *Ambio* **20**: 344–346.

ESRI. 2005. *ArcGIS 9.1*. ESRI Inc: Redlands, CA.

Evans J, Geerken R. 2004. Discrimination between climate and human-induced dryland degradation. *Journal of Arid Environments* **57**: 535–554.

Foster RH. 2006. Methods for assessing land degradation in Botswana. *Earth & Environment* **1**: 238–276.

Gao J, Liu Y. 2008. Mapping of land degradation from space: A comparative study of Landsat ETM+ and ASTER data. *International Journal of Remote Sensing* **29**: 4029–4043.

Hein L, de Rider N. 2006. Desertification in the Sahel: A reinterpretation. *Global Change Biology* **12**: 751–758.

Hengl T, Heuvelink GBM, Rossiter DG. 2007. About regression kriging: From theory to interpretation of results. *Computers & Geosciences* **33**: 1301–1315.

Lal R, Blum WH, Valentine C, Stewart BA. 1998. *Methods for Assessment of Soil Degradation*, Advances in Soil Science. CRC Press: Boca Raton, FL.

Lestrelin G. 2010. Land degradation in the Lao PDR: Discourses and policy. *Land Use Policy* **27**: 424–439.

Lestrelin G, Giordano M. 2006. Upland development policy, livelihood change and land degradation: Interactions from a Laotian village. *Land Degradation & Development* **18**: 55–76.

Metternicht G, Zinck JA, Blanco PD, del Valle HF. 2009. Remote sensing of land degradation: Experiences from Latin America and the Caribbean. *Journal of Environmental Quality* **39**: 42–61.

Muchiri PW. 2007. Climate of Somalia. FAO-SWALIM Technical Report No. W-01. FAO-SWALIM: Nairobi, Kenya. www.faoswalim.org

Nachtergaele F, Licona-Manzur C. 2006. The Land Degradation Assessment in Drylands (LADA) Project: Reflections on Indicators for Land Degradation Assessment. In *The future of drylands: international scientific conference on desertification and Drylands research*, Tunis, Tunisia, 19–21 June 2006.

Nachtergaele F, Petri M. 2008. *Mapping Land Use systems at global and regional scales for land degradation assessment analysis*. FAO: Rome.

Nicholson SE, Farrar TJ. 1994. The influence of soil type on the relationships between NDVI, rainfall, and soil moisture in semiarid Botswana. I. NDVI response to rainfall. *Remote Sensing of Environment* **50**: 107–120.

Nikken M. 1999. Wavelet analysis of rainfall-runoff variability isolating climatic from anthropogenic patterns. *Environmental Modelling & Software* **14**: 283–295.

Oduori SM, Vargas RR, Alim SM 2007. Land Use Characterization of a Selected Study Area in Somaliland. FAO-SWALIM Technical Report No. L-04. FAO-SWALIM: Nairobi, Kenya. www.faoswalim.org

Oldeman LR, Hakkeling RTA, Sombroek WG. 1991. *World map of the status of human-induced degradation: an explanatory note*. ISRIC: Wageningen, The Netherlands/UNEP, Nairobi, Kenya.

Omuto CT. 2008. Assessment of soil physical degradation in Eastern Kenya by use of a sequential soil testing protocol. *Agriculture, Ecosystems & Environment* **128**: 199–211.

Omuto CT, Vargas RR. 2009. Combining pedometrics, remote sensing and field observations for assessing soil loss in challenging drylands: A case study of northwestern Somalia. *Land Degradation & Development* **20**: 101–115.

Omuto CT, Vargas RR, Alim MS, Ismail A, Osman A, Iman HM. 2009. Land Degradation Assessment and a Monitoring Framework in Somalia. FAO-SWALIM Technical Report No. L-14. FAO-SWALIM: Nairobi, Kenya. www.faoswalim.org

Omuto CT, Vargas RR, Alim MS, Paron P. 2010. Mixed-effects modelling of NDVI-rainfall relationship for detection of human-induced loss of vegetation cover in the drylands. *Journal of Arid Environment* **74**: 1552–1563.

Pinheiro JC, Bates DM. 2000. *Mixed–effects model in S and S–plus*. Springer–Verlag: New York, NY.

du Plessis WP. 1999. Linear regression relationships between NDVI, vegetation and rainfall in Etosha National Park, Namibia. *Journal of Arid Environments* **42**: 235–260.

Prince SD, Becker-Reshef I, Rishmawi K. 2009. Detection and mapping of long-term land degradation using local net production scaling: Application to Zimbabwe. *Remote Sensing of Environment* **113**: 1046–1057.

R Development Core Team. 2010. *R: A language and environment for statistical computing*. R Foundation for statistical Computing: Vienna, Austria. http://www.R-project.org

Samatar AI. 1989. *The state and rural transformation in northern Somalia, 1884–1986*. The University of Wisconsin: Madison.

Shepherd KD, Palm CA, Gachengo CN, Vanlauwe B. 2003. Rapid characterization of organic resource quality for soil and livestock management in tropical agroecosystems using near-infrared spectroscopy. *Agronomy Journal* **95**: 1314–1322.

Sonneveld BGJS. 2003. Formalizing expert judgments in land degradation assessment: A case study for Ethiopia. *Land Degradation & Development* **14**: 347–364.

Stocking M, Murnaghan N. 2001. *Handbook for the field assessment of land degradation*. Earthscan Publishers: London.

Symeonakis E, Drake N. 2004. Monitoring desertification and land degradation over sub-Saharan Africa. *International Journal of Remote Sensing* **25**: 573–592.

Tefano P 1999. *The global environmental benefits of land degradation control on agricultural land: global overlays program*. The World Bank: Washington, DC.

Thiam KA. 2005. An evidential reasoning approach to land degradation evaluation: Dempster-Shafer theory of evidence. *Transactions in GIS* **9**: 507–520.

Tucker CJ, Pinzón JE, Brown ME, Slayback D, Pak EW, Mahoney R, Vermote E, El SN. 2005. An extended AVHRR 8-km NDVI data set compatible with MODIS and SPOT vegetation NDVI data. *International Journal of Remote Sensing* **26**: 4485–4498.

UNEP. 1992. *World Atlas of Desertification*. Edward Arnold: London.

Wessels KJ, Prince SD, Malherbe J, Small J, Frost PE, VanZyl D. 2007. Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa. *Journal of Arid Environments* **68**: 271–297.

Wessels KJ, Prince SD, Reshef I. 2008. Mapping land degradation by comparison of vegetation production to spatially derived estimates of potential production. *Journal of Arid Environments* **72**: 1940–1949.

Williams CA, Albertson JD. 2006. Dynamical effects of the statistical structure of annual rainfall on dryland vegetation. *Global Change Biology* **12**: 777–792.

WRB. 2006. World Reference Base for Soil Resources. World Soil Resources Reports, 103. FAO: Rome.