

Identification of Indicators for Desertification

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Abstract: Desertification is the consequence of a series of important degradation processes in semi-arid and arid regions, where water is the main limiting factor of land use performance on ecosystems. Environmental indicators can facilitate the assessment and monitoring of desertification by providing synthetic information on the status and trends of environmental processes leading to desertification. This paper analyses the importance of using indicators for defining areas vulnerable to desertification and the criteria for selecting indicators of desertification risk. Simple indicators related to the physical environment such as soil depth, slope gradient, slope exposure, parent material, rock fragment content, annual rainfall, aridity index, type of vegetation, plant cover, etc., and land management characteristics such as tillage operations, tillage depth, controlled grazing, period of exiting land use type, erosion control measures, etc., can be easily used for defining desertification risk. However, the use of indicators related to socio-economic characteristics of an area such as family size, farmer age, farm size, farmer income, land tenure, etc., should be treated very cautiously, analyzed at local conditions, and not generalized for other areas. The indicators become more effective when they are applied on the basis of land use type.

Key words: Desertification, indicator, environmentally sensitive areas, land use types.

Desertification, a series of natural processes leading to gradual land degradation, is one of the most serious environmental issues at global, national, regional and local scales (UNEP, 1992; Imeson, 1996). Land degradation means the reduction or loss of the biological and economic productivity and complexity of irrigated and non-irrigated agricultural lands, pastures, rangelands, forests and forested lands. Erosion represents a serious hazard for land degradation and desertification in dryland ecosystems, bringing about large reductions in vegetation growth, siltation of water courses, filling of valleys and reservoirs, and the formation of deltas along coastal areas. Erosion rates

attributed to surface water runoff vary widely. Values of 0.4 mm yr^{-1} to 1.7 mm yr^{-1} have been reported in the Mediterranean badlands (Yair *et al.*, 1982; Benito *et al.*, 1992). However, much higher soil losses of 0.4 to 1.4 cm per year have been measured for hilly cultivated areas in Greece due to tillage erosion caused by the use of cultivation implements, depending on slope gradient and land surface characteristics (Tsara *et al.*, 2001).

Salinization is another important process promoting desertification. In many cases, the rapid development resulted in the over-exploitation of the aquifer systems for a variety of uses, such as agricultural,

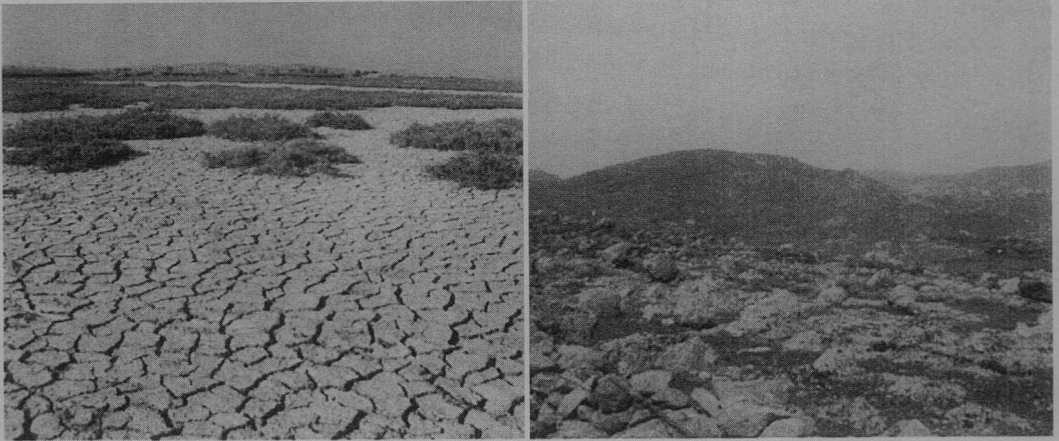


Fig. 1. Mediterranean areas desertified due to salinization (left) and due to soil erosion (right) (photos by C. Kosmas).

industrial and domestic, causing gradual intrusion of sea water in the aquifers. Irrigation using water with high salt concentrations increased the salinity of soil, causing an unproductive desertified land (Fig. 1). Soil salinization is a potential desertification threat for lands characterized by high xerothermic climatic indices (Kosmas, 1999). Moreover, as tourism continuously grows along coastal areas, water allocation is shifted towards domestic consumption. The increasing water consumption, combined with the substantial increase in water requirements associated with high input agriculture, is likely to create significant water allocation problem bringing about further degradation of the plains through salinization.

An assessment carried out by FAO, based on data collected under the project "Global Assessment of Soil Degradation – GLASOD" (Oldeman, 1988; Oldeman *et al.*, 1990), showed that 19.5% of drylands of the world have been affected by soil

degradation. According to FAO almost 40% of agricultural land has been adversely affected by human-induced soil degradation, and more than 6% is degraded to such a degree that restoration of its original productive capacity is possible only through major capital investments (Oldeman, 1994). Another study (Dregne *et al.*, 1991), carried out by the International Centre for Arid and Semi-Arid Land Studies (ICASALS, Texas), revealed that approximately 70% of arid lands show more or less intense signs of desertification. Desertification threatens over 1.5 billion people in the world, and affects a quarter of the world's land in more than 100 countries. Today desertification is spreading at a rate of some half a million hectares per year.

Since 1949 scientists have tried to define desertification as the creation of desert-like conditions resulting from erosion processes (Aubreville, 1949). The United Nations Convention for Combating Desertification (UNCCD) has defined desertification as

land degradation in arid, semi-arid and dry sub-humid areas, resulting from various factors, including climatic variations and human activities (UNEP, 1994). Areas affected by desertification are found in North and South America, Africa, southern Europe, Asia and Australia. In Africa over one billion hectares are affected by desertification.

Highly degraded and desertified land is demonstrably clear especially in dryland ecosystems (including arid lands covering about 12% of the earth's land surface, semi-arid occupying 17.7%, and dry sub-humid areas covering 10%), with entire landscape no longer able to sustain agriculture, and only relict patches of the indigenous forest cover remaining. Of course, this situation can not be attributed to recent technological exploitation of the natural resources, even though there is evidence of intensification of the processes of desertification in the last couple of decades. Large scale deforestation of hilly areas around the Mediterranean region, accompanied by intensive cultivation and overgrazing, has occurred some thousands of years ago (Marathanou *et al.*, 2000), resulted in accelerated erosion and the formation of badlands with very shallow soils. Soil erosion was reported first by Homer in his *Iliad*. The hilly desertified areas of Greece were originally forested and covered by a fertile soil which, however, was rather shallow and vulnerable to erosion. Upland grazing and farming in Greece probably began around the middle of the second millennium (BC) and was related to initial damage of the forests. Reduction in agricultural productivity is referred to by Plato (4th century BC), who notes the

occurrence of massive floods and landslides, the disappearance of forests and the denudation of cattle pastures in Attica, Greece. It is considered that salinization of productive land caused by over-irrigation may have hastened the decline of ancient civilization of Babylon. Archeological and geomorphological evidence from the badlands in southern Spain shows that the basic present physical characteristics, such as drainage patterns and slope morphology, exist in places for some 4000 years ago, so erosion cannot be considered as a human-induced disaster of recent times (Wise, 1982).

The forthcoming global climate change expects to cause a significant increase in the aridity of the climate for the next decades and desertification is expected to proceed at higher rates. The already existing arid, semi-arid and dry subhumid climatic conditions affect large areas with seasonal droughts. Very high inter-annual rainfall variability causes periods of particularly long drought and sudden and high-intensity rainfall. Under hot and dry climatic conditions the tolerance to erosion of shallow soils in dry badlands with poor vegetation cover is rather low, and rainfed vegetation can no longer be supported, leading to desertification. Climate changes such as increasing temperature and aridity tend to reduce the biomass production potentials, enhance erosion, increase land albedo and thus further increase air temperature and aridity. This is followed by a net decrease in carbon dioxide assimilation by the plants and thus it greatly contributes to climate change at the local and regional scales and to desertification in a broad sense.

Vegetation and land use are important factors controlling the intensity and the frequency of overland flow and water erosion. Extensive Mediterranean areas cultivated with rainfed crops such as cereals, vines and olives, are mainly confined to hilly lands with shallow soils, which are very sensitive to erosion. Rainfall amount and distribution are the major determinants of biomass production (Kosmas *et al.*, 1993; Kosmas *et al.*, 1997). These areas become vulnerable to erosion and desertification due to: (a) the reduced protection of the ground surface by vegetation from heavy rains with high intensity; (b) the reduction of infiltration rate due to the compaction from farm machinery; and (c) the formation of soil surface crust.

In the early years there was a lack of a common knowledge of "what to measure" and "how to measure" land degradation and desertification. Already in 1930's, Storie (as reported by Singer and Ewing, 2000) proposed an index as a multiplication of a series of factors representing soil characteristics such as soil texture, morphology and sodicity, drainage class, slope, etc. Each characteristic was rated according to given tables and an index was derived. Later, in the early 1940's, the first approach in predicting soil erosion appeared through equations that expressed the effect of slope length, steepness and conservation practices on soil erosion. In 1947, a soil factor and a climate factor (Musgrave equation) were also considered (Laflen *et al.*, 1997) for soil erosion. In the 1970's, indicators were used to measure the advance of the desert, using both biophysical and socio-economic parameters, such as lack of food, population movements, etc. (Enne and Zucca, 2000).

The interaction of the complex and fast changing environmental, economic and social issues requires as far as possible a clear view of these interrelations. The main means of communicating the pertinent information is through indicators. The identification of the most efficient indicators is, therefore, extremely important in the context of combating desertification. The necessity of elaborating indicators is one of the priorities identified by UNCCD. The Convention considers indicators as the appropriate tool to provide operational support to a wide range of activities such as assessing and mapping the extent of desertification, as well as determining the causes, quantifying the impacts, justifying expenditure for mitigation measures and monitoring the efficiency of the measures undertaken.

Indicators Used to Define Desertification Risk

Main characteristics of indicators

Several descriptions and definitions of the term "indicator" have been given by various agencies. The European Environmental Agency (EEA) has considered that an indicator can be defined as a parameter or value derived from parameters, which provides information about a phenomenon (OECD, 1993; EEA, 1998). In this sense indicators should not be confused with raw data from which they are derived. Indicators are quantified information which help to explain how things are changing over time and space (EEA, 1998). Indicators generally simplify the reality in order to make complex phenomena quantifiable, so that information can be communicated (Department of

Environment, UK, 1996; EEA, 1998). It should be added at this point that when a complex process has to be described (for example the process of soil erosion), a single indicator is generally not sufficient, and several indicators would be necessary, even if not many, but organized into a precise set. In particular, an environmental indicator is a parameter, which provides information about the situation or trends in the state of environment in the human activities that affect or are affected by the environment, or about relationships among such variables (US EPA, 1995; EEA, 1998).

Many international and national organizations now recognize that environmental indicators are playing an increasingly important role in supporting development policies. The OECD (1993) has defined the following three basic criteria for developing indicators: (a) policy relevance and utility for users (indicators must provide a representative picture, simple and easy to interpret, and comparable), (b) analytical soundness (indicators must be scientifically and technically well founded), and (c) measurability (indicators must be based on data readily available, well documented, updated at regular intervals).

According to Lopez-Bermudez and Barbera (1998) indicators must be characterized by the following minimum requisites: (a) to be based on the best available scientific knowledge on geocological and socio-economic systems, (b) to summarize the state of the system and/or future trends, (c) to be relevant to environmental problems related to decision-making, and (d) to be feasibly gathered and processed.

For the identification and evaluation of indicators a series of characteristics have

been proposed by various authors (Riley, 2001; Stein *et al.*, 2001). The selected indicators have to be: (a) objectively and scientifically measurable, (b) preferentially quantitative, (c) easy and cost-effective to be measured, (d) adapted to Mediterranean conditions, (e) sensitive to environmental changes, (f) simple in concept and accessible to both specialists and land managers, and (g) able to support policy decisions.

The above discussion shows the necessity for identifying a set of indicators of desertification based on scientific criteria in order to guarantee a close and real relationship between the indicator and the state or trend that it represents. One core question about indicators is their feasibility and usefulness. The most appropriate indicator is not that provides best information about the state and future trends for desertification, but the one that takes into account the available information and knowledge under low cost (Lopez-Bermudez and Barbera, 1998). It is rather difficult to identify "perfect" indicators describing desertification risk. It is preferable to work with a set of indicators informing about different aspects and conditions. For example, a complex system is badly summarized by only one variable with high temporal and spatial variation. Sorlini and Amadio (1998) mentioned that identification of a set of indicators is a complex issue due to numerous causes of desertification of a piece of land. Furthermore, macroscale indicators may be too much coarse to identify small-scale changes. The cause-effect relations are complex and sometimes difficult to be identified.

Having in mind all the above mentioned difficulties for identifying appropriate indicators of desertification, it is necessary to implement a flexible strategy that takes

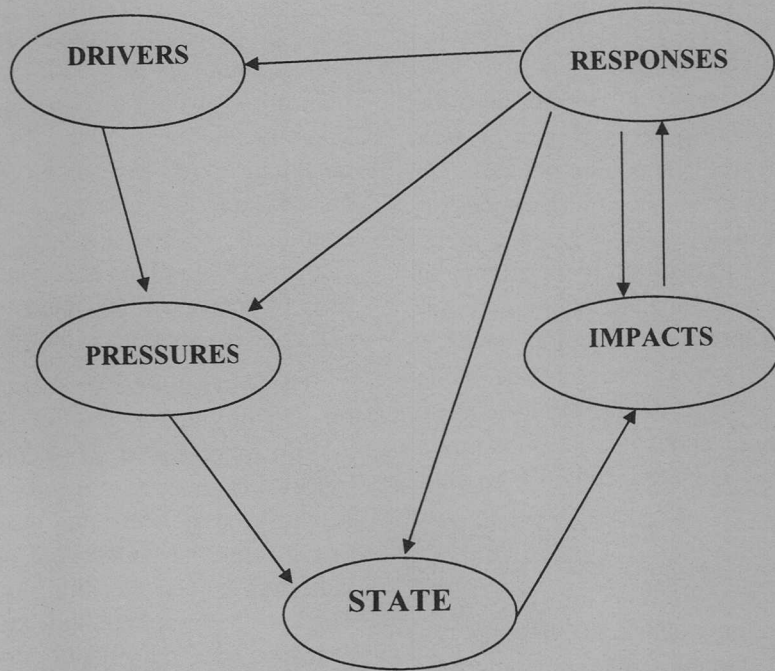


Fig. 2. DPSIR framework for system conditions used for classifying indicators (EEA, in Gentile, 1998).

into account all these problems. The strategy can be based on the following principles (Lopez-Bermudez and Barbera, 1998): (a) exploitation of easily available information, (b) characterization of desertification, first at regional scale and then at local scale, (c) selection of indicators most directly related to the problem, (d) considering singularities of agroecosystems, (e) utilization of indicators that link biophysical aspects to socio-economic ones, and (f) emphasizing those aspects more relevant from the socio-economic point of view.

Classification of indicators

Many authors (O'Connor, 1994; Pieri *et al.*, 1995; SCOPE, 1995; Dumanski and Pieri, 1996) considered that classification

of indicators must take into account the linkages between: (a) pressures exerted on the environment by human activities, (b) changes in quality of the environmental components, and (c) societal responses to these changes that can be a useful and valuable tool for land-users and policy makers. In this context, the DPSIR framework (Driving forces, Pressure, State, Impact, Response) has been proposed (Fig. 2). In this scheme indicators can be briefly delineated as a chain reaction process, starting from a developmental effort of natural resources, which applies Pressures and Driving forces on the system, changing consequently the State of the system. Such a change produces Impacts, which lead to Responses that, by a feed back loop, interact

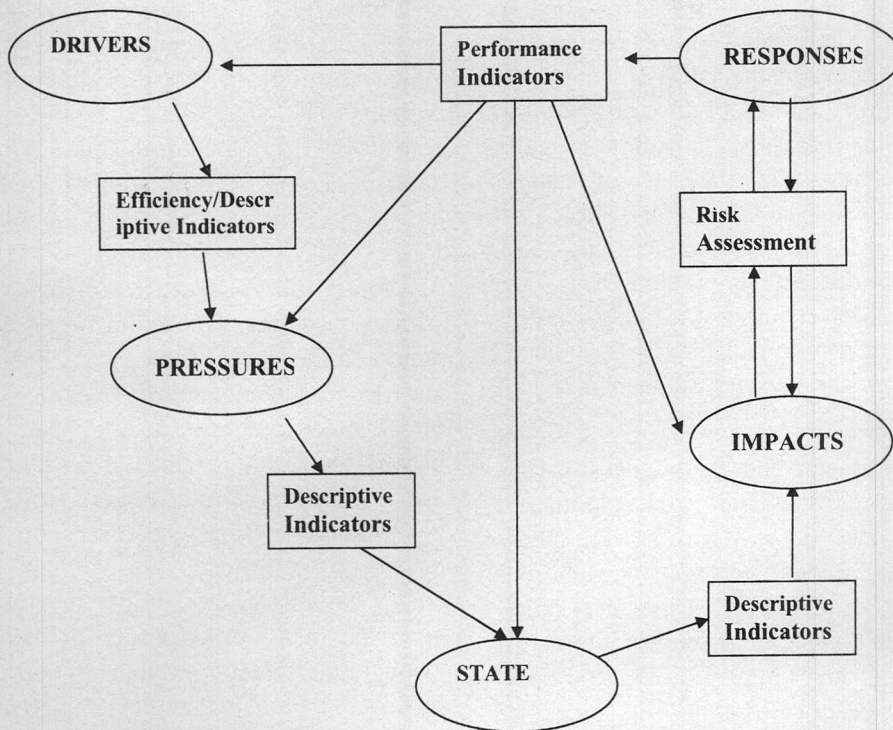


Fig. 3. DPSIR elements and related indicators (EEA, in Gentile, 1998).

with the Driving forces, the Pressures, the State and the Impacts. In this regard, the policy makers need information for all the steps in the presented framework. The vehicles that may convey and reflect such information are indicators.

The DPSIR framework may be utilized as representing the interrelations and their sequences among the initial condition of the system, its transformation and the resulting conditions eliciting from Impacts and Responses. According to their structure, indicators may be grouped into four major categories demarcated as follows: descriptive, performance, efficiency, and total welfare indicators. Figure 3 represents the indicators categories that link the various

DPSIR elements. Descriptive indicators present the existing conditions, the context of system elements or issues in relation to the principal characteristics (time, geographical local, etc.) through which such elements may be expressed. They may be Driving forces, Pressure, State, Impact, or Response indicators.

In this context, driving forces indicators may delineate the economic, social and demographic conditions in a given time frame of a certain area. Such indicators also present the resulting changes in production, life styles and consumption. In this regard, the principal driving forces are population growth and the changes in economic and social modes. Such driving

forces are creating the corresponding changes in consumption and production. Thus, according to the DPSIR chain these driving forces are applying pressure on the system. Pressure indicators usually express changes in the use of natural resources (water, land, minerals), biological and natural agents, emissions, etc. Therefore, the pressures applied by the economic and social frame and practices to the physical system resulted in the induced changes in the system elements.

State indicators demarcate the status of various parameters in a given local situation. They may present biological parameters (wildlife resources, fish stocks, etc.), chemical parameters (nitrogen, phosphorous concentrations in the soil or in water bodies, etc.), or the quality and quantity of climatic parameters (rain, temperature, etc.). Impact indicators describe the impacts provoked by the changes of the state of the system. Impacts are generated on resource availability, biodiversity, economic relationships, social functions etc. Response indicators are associated and describe applied measures by societal groups or institutional organizations to confront, overcome, predict and prevent, compensate and adapt to the transformations of the state of the system. In addition, response indicators delineate policy measures to preserve certain desirable system features. Such features may lead to "negative driving forces", since their objective is to relieve the pressure and not to cause changes in the state of the system.

Theoretically all soil properties depend on the five soil forming factors (parent material, climate, topography, organisms

and time) (Jenny, 1980), which describe the general environment of the soil and which are more or less the same as those defining the land. Therefore, soil can be considered as a dominant factor of desertification. Several authors (Allan *et al.*, 1995; Doran *et al.*, 1994; Doran and Jones, 1996; Karlen *et al.*, 1997) have developed the concept of soil quality for various purposes. One main purpose is to approach the public for creating a broader and deeper understanding of soils as one of the main media, besides air and water, in sustainable environmental development. The need for basic indicators of soil quality is assumed by the questions commonly posed by farmers, researchers, and conservationists. For example, one question is "what measurements should I make to evaluate the effects of management on soil function now and in the future?" Soil quality can be used not only as a management tool or aid for farmers but also as a measure of sustainability of land management systems. A soil quality index is needed to identify low production areas, to make realistic estimates of food production, to monitor changes in sustainability and environmental quality as related to agricultural management, and to assist federal and state agencies in formulating and evaluating sustainable agricultural and land-use policies (Granatstein and Bezdicsek, 1992). Our ability to identify basic soil properties that serve as indicators of soil quality is complicated by the many physical, chemical, and biological factors involved and their varying interactions in time, space, and intensity (Larson and Pierce, 1991; Rodale Inst., 1991; Papendick and Parr, 1992; Pierce and Larson, 1993). However,

one way to start is by identifying a basic list of measurable soil properties that define the major processes functioning in soil and ensure that the measurements we are making reflect conditions as they exist in the field.

According to Doran and Parkin (1994) basic soil quality indicators should also be sensitive to variations in management or climate in order to monitor changes in soil quality and propose management changes to enhance soil quality. Some authors (Acton and Padbury, 1993; Acton and Gregorich, 1995) defined soil quality attributes as measurable soil properties that influence the capacity of soil to support crop production or to perform environmental functions. Soil attributes are useful in defining soil quality criteria and serve as indicators of change in quality. Attributes that are very sensitive to soil management are most desirable as indicators such as soil depth, soil organic matter and electrical conductivity, which are affected by soil degradation processes (Arshad and Coen, 1992).

Possible descriptive indicators to characterize and monitor soil quality are given by Arshad and Coen (1992) and Reganold *et al.* (1992), including surface crusting, evidence of erosion, ponding of water, vegetative cover, soil structure, friability, and consistence. Other authors (Piccolo, 1996; Reeves, 1997) consider organic matter content as a very important soil quality indicator.

Angelakis and Kosmas (1998) have proposed a series of indicators related to soil erosion and water availability for defining areas vulnerable to desertification. Based on these indicators, the land capability

to withstand further degradation, or the land suitability for supporting specific types of land use is assessed. These indicators can be classified into six broad categories related to soil, water, vegetation, society and land management. Indicators related to soil are texture, slope gradient, parent material, rock fragment content, drainage, and aggregate stability. Water includes mainly indicators related to quality (electrical conductivity) and availability. The most important indicators related to climate are precipitation, evapotranspiration and aridity. Society includes indicators such as land and water use, training status and habits, customs and traditions. In the management are considered indicators related to existing policies for environmental protection and the degree of enforcement of such policies, infrastructures, and existing technology. Of course, when considering all these indicators some overlapping and intercalations exist among the various indicators, complicating the application of indicators for assessing desertification vulnerability of an area. Furthermore, indicators related to society and management cannot be easily generalized for broad areas.

Yassoglou (2002) has considered a series of soil attributes affecting desertification risk. These attributes can be easily assessed at field level or are available in regular soil survey reports, including low surface stoniness (%), severe and extreme erosion state, extensive surface capping, shallow and very shallow rootable depth, slow and very slow water infiltration rate, no or weak or platy soil structure, shallow depth and low permeability of subsurface horizon or layer, no surface litter, thin or low organic matter in surface horizon, low available

water holding capacity, low fertility, high electrical conductivity, shallow petrocalcic horizon, and shallow continuous hard bedrock. The above properties can be grouped into the following three principal states of soil degradation that lead to desertification: the severely reduced rootable soil space, soil salinity and surface crusting. Karlen and Stott (1994) presented a framework for evaluating site-specific changes in soil quality where a high quality soil is defined as the one that: (i) accommodates water entry, (ii) retains and supplies water to plants, (iii) resists degradation, and (iv) supports plant growth.

Soil erosion is one of the most important processes leading to desertification. Soil degradation due to soil erosion is a serious threat to the soil quality and productivity. The effects of soil erosion on productivity depend largely on the thickness and quality of the topsoil and on the nature of the subsoil (Frye *et al.*, 1985; Acton and Padbury, 1993). Productivity of deep soils with thick topsoil and excellent subsoil properties may be virtually unaffected by erosion. However, most hilly soils are shallow or have some undesirable properties in the subsoil such as petrocalcic horizon, or bedrock that adversely affects yields. Therefore, as Fierotti and Zanchi (1998) have pointed out, the degree of soil erosion can be considered as a global indicator. But to determine the degree of soil erosion is not an easy task. The existing predictive models assess soil erosion, but the efficacy in the various situations and at different operational scales have not been tested yet. By using erosion models in combination with other specific indicators such as the development and intensity of erosive forms,

the trend of various physical characteristics of the soil, the organic matter content, the vegetation growth rate, the degree of vegetation cover and its productivity can be valuable tools in defining desertification risk.

Description of selective indicators of desertification risk

For a strategy of action against desertification, it is essential to adopt a nested approach so that environmentally sensitive areas (ESAs) to desertification are easily identified and mapped by using available resources in a cost-effective manner. It is essential to adopt a uniform, objective and scientifically based methodology which identifies regions where the risk of desertification is higher. A methodology has been proposed by Kosmas *et al.* (1999, 2002) based on the identification of ESAs to desertification. The various types of ESAs can be identified and mapped by using certain key indicators or parameters for assessing the land capability to withstand further degradation, or the land suitability for supporting specific types of land use. The key indicators for defining ESAs to desertification are divided into four broad categories defining the qualities of soil, climate, vegetation and land management (Fig. 4).

Parent material is considered as a soil-forming factor affecting soil properties, plant growth (Kosmas *et al.*, 1993), soil erosion and ecosystem resilience. Soils derived from different parent materials react differently to vegetation, soil erosion and desertification (Yassoglou and Kosmas, 1990; Kosmas *et al.*, 2000). Hilly soils formed on consolidated parent materials such as limestone, sandstone, volcanic lava, etc.

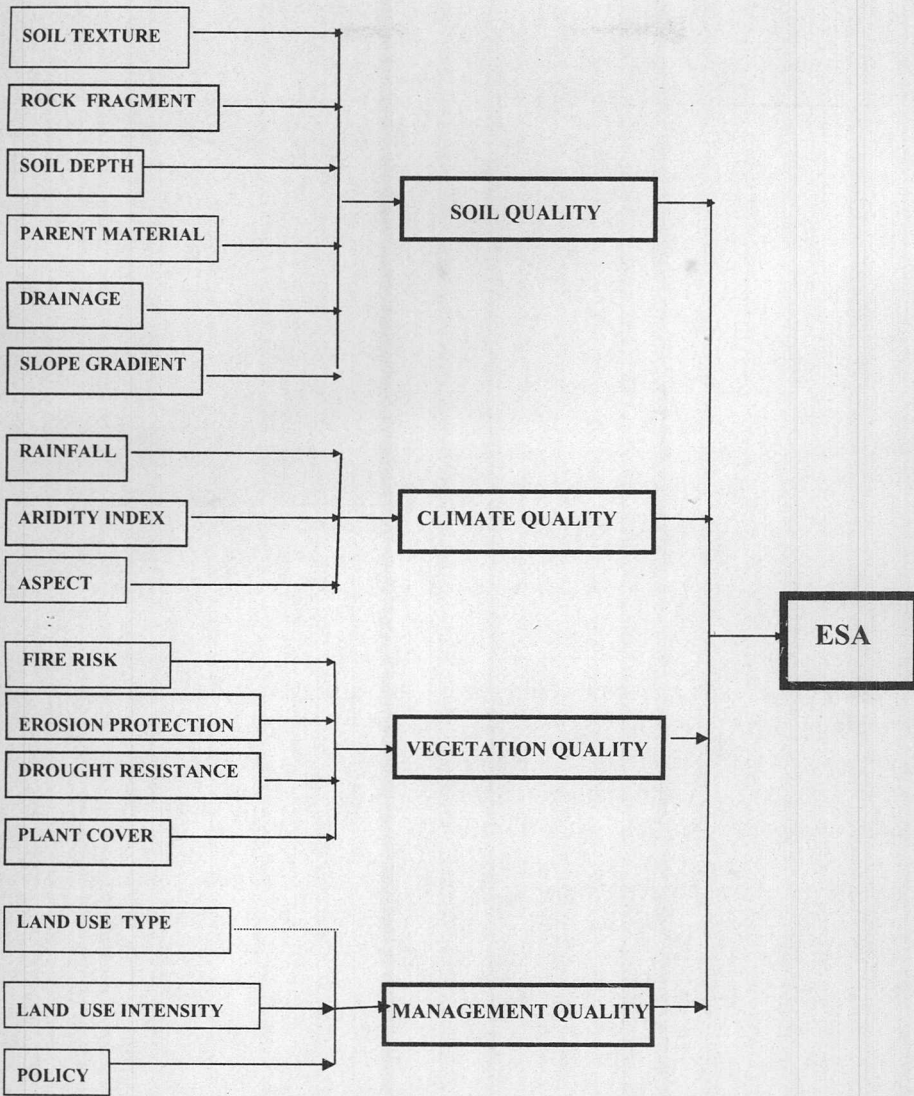


Fig. 4. Parameters used for the definition and mapping of the ESAs to desertification (Kosmas et al., 1999).

usually have a restricted effective rooting depth as the soils are eroded and shallow, characterized by high erodibility and slow vegetation recovery. Under hot and dry climatic conditions, rainfed vegetation may not be supported in such areas, leading to desertification.

Soil depth is a very important indicator for both the state and the potential risk of desertification. Any degrading process that limits the rootable soil space depletes its nutrients and water supply capacity and reduces bioactivity (Yassoglou, 2002). This indicator depends on several soil and

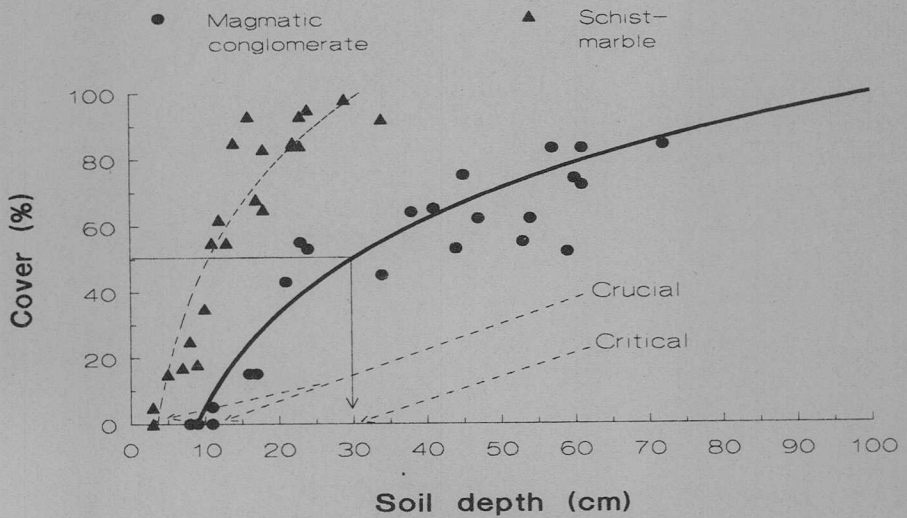


Fig. 5. Relation of percentage vegetation cover of *Sarcopoterium* sp. and soil depth measured in areas with soils formed on pyroclastics (magmatic conglomerates) and schist-marble (Kosmas *et al.*, 2000).

environmental parameters. Among them are: soil texture, structure, organic matter, mineralogy, water holding capacity, stoniness, parent material, slope angle, aspect, climate and soil formation rate.

Given certain soil physical characteristics and underlying parent material, two soil depths, very important for land protection, can be distinguished: the critical and the crucial soil depth. The critical depth can be defined as the soil depth in which plant cover achieves values above 40% (Fig. 5). Extensive studies conducted under semi-arid climatic conditions in hilly areas with soils formed on various parent materials have shown a critical depth of 25 to 30 cm (Kosmas *et al.*, 2000). On soils less than that depth the recovery of the natural perennial vegetation is very low and the erosional processes may be very active, resulting in further degradation and desertification of the land. When a hilly landscape of marginal capability is cultivated, agriculture should

be abandoned before the soil reaches the critical depth.

While the critical depth is a limit to cultivation, the crucial depth can be defined as a lesser soil depth on which perennial vegetation can no longer be supported, and the whole soil is rapidly washed away by wind or water erosion. This is an irreversible process. Crucial depth is affected by the type of parent material in which soil is formed. Soils formed on pyroclastics are the most sensitive in their capability, with a crucial soil depth of 10 cm, below which vegetation can not be supported (Kosmas *et al.*, 2000). Soils formed on schist-marble metamorphic rocks have a higher capability to support perennial vegetation under the same climatic conditions, with crucial soil depth of around only 4 to 5 cm.

Rock fragments have a great but variable effect on soil erosion (Poesen *et al.*, 1994;

Danalatos *et al.*, 1995), and soil water conservation (van Wesemael *et al.*, 1995; Moustakas *et al.*, 1995) and biomass production (Poesen and Lavee, 1994), so playing an important role on land protection from desertification. Generally, runoff and sediment loss are greater from stony than stone-free soils, apart from soils rich in coarse gravel on the surface subjected to heavy and prolonged showers. Bunte and Poesen (1993) found that inter-rill sediment loss increased with increasing rock fragment percentage up to about 20%. Furthermore, rock fragments present on the soil surface restrict soil water evaporation, protecting areas from desertification (Danalatos *et al.*, 1995).

Slope angle and generally topography are undoubtedly important determinants of soil erosion. Erosion becomes acute when slope angle exceeds a critical value and then increases logarithmically. Based on a study conducted by Kosmas *et al.* (1998) in the island of Lesbos (Greece) it appears that slope grade has a variable effect in different climatic conditions, depending on annual rainfall. The probability of high erosion decreased with increasing rainfall for the same slope classes.

Deterioration of the soil structure, under specific conditions, may cause the formation of crust on the soil surface (Yassoglou, 2002). Surface crust contributes to the desertification of land in two ways: by restricting the emergence of germinated plants, and by reducing water infiltration. The latter has two prominent negative effects on sloping terrain: reduction of soil water available to plants and increased runoff and consequently increased rates of soil loss. Soil structure stability is affected by various factors such

as change in organic matter content, use of heavy machinery, irrigation with poor quality water, etc.

Arid, semi-arid, and dry-subhumid climatic conditions are characterized by a seasonal climate and specific ecological and pedological conditions, which make its ecosystems the most vulnerable due to the fragility of the environment and the low rates of biomass production during dry periods. Lavee *et al.* (1991) have shown that infiltration rates become lower and the soil erodibility increases as climatic conditions become drier. The uneven annual and interannual distribution of rainfall, and the occurrence of extreme events are the main climatic factors contributing to the degradation of the land. The prevailing weather conditions during the growing period of annual crops may be so adverse that the soils remain bare, creating favorable conditions for overland flow and erosion. Any loss of volume of marginal lands greatly reduces the potential for biomass production, ultimately leading to desertification. Desertification at present threatens only the shallow and severely eroded soils. Global climatic change may threaten the majority of the areas under the above climatic conditions.

Soil erosion data collected from various sites along the northern Mediterranean region show that the amount of annual rainfall of 280 to 300 mm has a crucial effect in increasing runoff (Kosmas *et al.*, 1997). There is a tendency of increasing runoff and sediment loss with decreasing rainfall in hilly Mediterranean shrublands, especially in the region where rainfall is greater than 300 mm (Fig. 6). Below 280 mm annual rainfall limit, runoff and sediment loss decrease with decreasing rainfall.

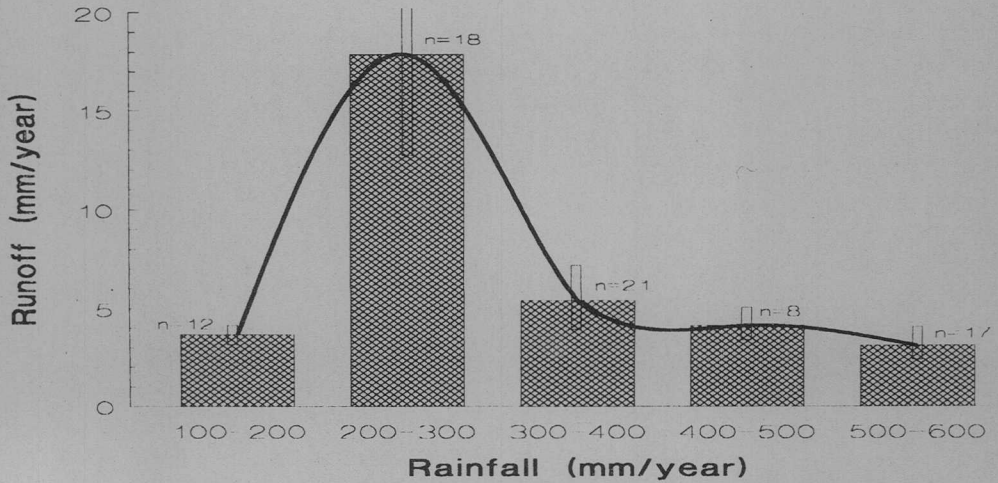


Fig. 6. Relationships between run-off and annual precipitation measured at four Mediterranean sites under shrubland (Kosmas *et al.*, 1997).

Rainfall amount and distribution are the major determinants of biomass production on hilly lands under semi-arid climatic conditions. Decreasing amounts of rainfall combined with high rates of evapotranspiration drastically reduce the soil moisture content available for plant growth. Reduced biomass production, in turn, directly affects the organic matter content of the soil and the aggregation and stability of the surface horizon against erosion (Kosmas *et al.*, 1993). Aridity is a critical environmental factor in determining the evolution of natural vegetation, especially through water stress which may result in reduced vegetation cover. However, the existing vegetation in areas sensitive to desertification presents a great capacity of adaptation and resistance to dry conditions, and many species can survive many months through prolonged droughts with soil moisture content below the theoretical wilting point.

Slope aspect is considered an important factor for land degradation processes. Slope aspect affects the microclimate by regulating

the angle and the duration at which the sun rays strike the surface of the soil. In the Mediterranean region slopes with south and west facing aspects are warmer and have higher evaporation rates and lower water storage capacity than north and east facing aspects. Therefore, a slower recovery of vegetation is expected in southern and western aspects and high erosion rates than in northern and eastern aspects. As a consequence, southern exposed slopes usually have a lower vegetation cover than northern exposed slopes (Poesen *et al.*, 1998). The degree of erosion measured along north- and south-facing hillslopes is twice as much as or even higher in the south-facing slopes under various types of vegetation cover (Kosmas *et al.*, 2000).

The rate of soil degradation is also affected by the rate of vegetation degradation, which in turn is influenced by adverse climatic conditions (Langbein and Schumm, 1958; Grainger, 1992; Kosmas *et al.*, 1997). Key indicators of desertification related to the existing natural

or agricultural vegetation can be considered in relation to fire risk and ability to recover, erosion protection offered to the soil, drought resistance and percentage plant cover (Kosmas *et al.*, 1999). The loss of vegetation after fire and the progressive inability of soils to regenerate adequate vegetation cover due to erosion has already led to severe degradation and desertification of extensive hilly areas. Erosion rates seem to be enhanced after fires. The increased erosion rates are only partly due to the removal of vegetation. More important seems to be the formation of an impermeable subsurface layer, which decreases infiltration rates, while causing a quick saturation of the upper layers, leading to overland flow and erosion (Giovannini and Lucchesi, 1993). In contrast, aggregate stability increases after fire and that increase is more pronounced after severe burns (Molina, 1993).

Pastures in the Mediterranean region are also frequently subjected to man-induced fires in order to renew the biomass production. The vegetation found in Mediterranean type of climate is highly inflammable and combustible due to the high content of resins or essential oils in many species. Shrubby natural vegetation is known to have a high ability to recover after fire (Trabaud, 1993) and the environmental problems related to fire normally last for only a limited number of years after the fire incident. Apart from the fire and site characteristics, there are other parameters, which affect the process of the recovery, Human interference such as livestock grazing or change in the land use pattern may damage irreversibly the recovering vegetation (Clark, 1996).

Vegetation and land use are clearly important factors controlling the intensity and the frequency of overland flow and surface wash erosion (Bryan and Campbell, 1986; Mitchell, 1990). Extensive areas cultivated with rainfed crops such as cereals, vines, almonds and olives are mainly confined to hilly lands with shallow soils very sensitive to erosion. These areas become vulnerable to erosion and desertification because of the decreased protection by vegetation cover in reducing effective rainfall intensity at the ground surface (Faulkner, 1990). The main factors affecting the evolution of vegetation in arid, semi-arid and dry-subhumid climatic conditions, in the long term, are related to the irregular and often inadequate supply of rain water, the long length of the dry season, and perhaps fire and grazing (Clark, 1996). The main response of the plants to increased aridity is the reduction in leaf area index. Natural and semi-natural ecosystems dominated by evergreen sclerophyllic species are well adapted to Mediterranean climatic and landscape conditions. Extreme climatic conditions and human action can cause disequilibrium of these systems.

Vegetation cover plays a key role in land degradation (Francis and Thornes, 1990), and in fact, reduction in the perennial cover is regarded as an indicator of the onset of desertification (Thornes, 1996). Vegetation cover may be altered radically by man within a short time, but physical and biological changes within the soil, affecting erosion rates, may take longer periods (Ruiz-Flano *et al.*, 1992; Martinez-Fernandez *et al.*, 1995, 1996). Vegetation cover is crucial for controlling runoff

generation and can be readily altered along the hilly areas depending on climatic conditions and the period of the year. Many studies have shown that the variation in runoff and sediment yields in drainage basins can be attributed to the vegetation cover and land use management changes (Douglas, 1969; Reed, 1971; Patton and Schumm, 1975; Newson, 1985; Bryan and Campbell, 1986). Many authors have demonstrated that in a wide range of environments both runoff and sediment loss decrease exponentially as the percentage of vegetation cover increases (Elwell and Stocking, 1976; Lee and Skogerboe, 1985; Francis and Thornes, 1990).

The process of land degradation proceeds also with the reduction of organic matter content in the topsoil and the subsequent rapid decrease in soil biological activity. Large-scale deforestation of hilly areas, followed by intensive cultivation, and burning of the vegetation result in a drastic reduction of the organic matter content and the aggregate stability of the surface soil horizon (Danalatos, 1993). Land use change greatly affects organic matter content, aggregate stability and soil structure. For example, the shift from olive trees to vine cropping had a degrading effect on the organic matter content and the aggregate stability (Kosmas *et al.*, 1995).

Livestock is one of the main agricultural activities in several hilly areas and it is considered as one of the causes of land degradation and desertification (van der Leeuw, 1998). The process of land degradation can be greatly accelerated by high density of livestock which leads to vegetation degradation and, in turn, to soil compaction. The high grazing intensity

during the summer, when plant cover is restricted, promotes further reduction of plant cover, increasing soil erosion, and desertification risk (Schnabel, 1997). Once the land is devoid of vegetative cover and the soil is loosened, the torrential rains of autumn and winter begin to wash away the topsoil (Evans, 1998). Shepherds often damage natural vegetation by deliberately setting fire to eradicate vegetation and encourage the growth of new grass, which the livestock subsequently overgraze (Enne *et al.*, 1998).

Tillage erosion has been identified in several cases as a major process of soil degradation in hilly areas. Several experiments have been carried out to estimate the rate of tillage erosion under various management practices and tillage implements (Martini, 1953; Revel *et al.*, 1989; Lindstrom *et al.*, 1992; Govers *et al.*, 1994; Kiburys, 1995). Soil redistribution by tillage may often exceed soil redistribution by water runoff in rolling agricultural landscapes (Quine *et al.*, 1994; Quine *et al.*, 1996; Govers *et al.*, 1996; Quine *et al.*, 1997). Redistribution of topsoil from the upper landscape positions by the various tillage operations reduces significantly the effective soil depth and the water holding capacity (Blevins *et al.*, 1971; Tolnerr *et al.*, 1984; Singh *et al.*, 1998, Kosmas *et al.*, 2001; Gerontidis, *et al.*, 2001) which is the most serious long-term loss, restricting production (Danalatos, 1993; Kosmas *et al.*, 1993). Important indicators related to soil erosion and desertification are tillage depth, and tillage direction.

Based on the principles in defining indicators mentioned above, a list of

potential indicators (Table 1) was defined and analyzed in various types of land uses in areas affected by desertification in Greece in the frame of the European Research project DESERTLINKS. Classes and values have been defined for each indicator based on existing classification systems such as the European georeferenced database (Kosmas, unpublished data). Data have been collected in areas presenting various sensitivity to desertification and under the following four types of land use: (a) pastures, (b) olive groves, (c) wheat, and (d) pine forests. A principal component analysis was conducted for defining the most important indicators related to desertification for the study of land use types.

As Table 1 shows, the most important indicators for the olive groves were related to land management such as tillage operations, tillage direction, tillage depth, available water, water quantity and quality, presence of terraces, protection of terraces, sustainable farming, and frequency of flooding. Slope gradient was the most important indicator from the physical environment for olive groves. Important indicators for pastures were mainly related to the physical environment such as soil depth, slope gradient, and rock fragment content on the soil surface. Farm size was the only important indicator related to management for pastures. Physical indicators important for the pine forests were plant cover, soil drainage, parent material, and presence of rock fragments on the soil surface. Policy enforcement was the most important indicator related to land management and application of the existing regulations for protection of the environment in pine-forested areas. The most important indicators for areas cultivated with wheat were related to land

management characteristics, as in the olive groves, such as tillage direction, water available, water quantity and quality, frequency of flooding, land use intensity and policy enforcement (Table 1). Slope gradient and slope exposure were the most important indicators from the physical environment for this type of land use.

Environmental indicators can facilitate the assessment and monitoring of desertification at regional and local levels, as they provide synthetic information on the status and trends of environmental processes leading to desertification. However, the use of indicators related to socio-economic characteristics of an area should be treated very cautiously, analyzed at local conditions, and may not be generalized for other areas. Many scientists still believe that indicators are very crucial, but difficult too, to convey and communicate all the necessary relevant information in a system and society interactions and transformations. Few methodologies that have been developed using indicators may constitute a useful and valuable tool for land-users and policy makers for combating desertification.

As it has been reported previously, several efforts have been made for identification of indicators defining desertification risk. A limited effort has been made to determine threshold values or critical limits for the proposed indicators. Critical limits will vary with each indicator. For some indicators a 10% increase or decrease may be significant while others may not be affected by a 20% decline (Arshad, 2002). Selection of key indicators and their threshold values are required to monitor changes (direction, rate, magnitude,

Table 1. Important indicators of desertification (indicated by +) for various land use types defining areas sensitive to desertification in Greece

Indicators	Land use types			
	Olives	Pastures	Pines	Wheat
Type of ownership				
Farm size		+		
Number of parcels				
Parallel employment				
Farmer age				
Subsidies				
Tillage operations	+			
Tillage depth	+			
Tillage direction	+			+
Application of fertilizers				
Number of animal grazing				
Present type of land use				
Previous type of land use				
Period of existing type of land use				
Plant cover			+	
Soil depth		+		
Slope gradient	+	+		+
Drainage			+	
Soil texture				
Parent material				
Rock fragment content		+	+	
Rainfall				
Aridity index				
Slope exposure				+
Water available	+			+
Water quality	+			+
Water quantity	+			+
Frequency of flooding	+			+
Sustainable farming	+			
Presence of terraces	+			
Protection of terraces	+			
Controlled grazing				
Crop water requirements				
Erosion control measurements				
Policy enforcement			+	+
Fire risk				
Soil erosion protection				
Drought resistance of plants				
Land use intensity				+

extent, etc.) and determine trends in improvement or deterioration in land quality for various ecosystems (Arshad, 2002). More research is required on this issue.

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