A REMOTE SENSING-GIS APPROACH TO MONITORING REGENERATION AND PREDICTING RISK OF EROSION AND DESERTIFICATION AFTER A FOREST FIRE IN THE MEDITERRANEAN REGION

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ABSTRACT

A GIS-based decision support system has been developed to monitor the recovery of forested areas in the Mediterranean region destroyed by wildfires and to predict their potential for natural regeneration, risk of soil erosion, and risk of desertification. The system is configured on a set of decision rules that are applied to a prescribed set of ground and remote sensing data acquired from selected burnt wildland areas in Greece and subsequently used in the generation of risk maps for fire-affected regions. An accuracy greater than 90% was achieved for predicting regeneration potential and risk of erosion and desertification within plus or minus one classification category for the test areas studied.

1. INTRODUCTION

Each year, hundreds of thousands of hectares of forest and shrublands are destroyed by fire in the Mediterranean region, with an average of 535,000 hectares per year being burnt in Greece, Spain, Portugal, Italy, and southern France between 1980 and 1987 alone. The impact of wildland fires, along with improper land use and over-grazing, threaten approximately 60% of the land in southern Europe with desertification, as a result of the loss in vegetation cover and subsequent soil erosion.

The destruction of a vegetation cover by fire exposes the once protected underlying soil substrate to the combined effects of strong, dry winds that prevail in summer and frequent and intense rains that occur in winter in the Mediterranean region, markedly increasing the susceptibility soil to erosion. If left unprotected, the often thin and fragile soils are at risk of being quickly eroded, especially in hilly or mountainous terrain, thereby giving rise to a process of land degradation that can ultimately lead to desertification. As the most common form of regeneration of the forests is by natural re-seeding, the absence of a stable topsoil layer precludes the re-establishment of a forest.

There is a need, therefore, to be able to ascertain the amount of green vegetation remaining after a fire and to determine the level of recovery in the years immediately following it. Based on this information and the geology and topography of the area, a prediction of a burnt site's potential for natural regeneration and hence risk of erosion and desertification can be made, from which a decision to either undertake reforestration or allow natural regeneration can be taken.

2. OVERVIEW

The first few years after a fire are often decisive as to whether the vegetation in a burnt area is able to recover sufficiently to prevent a significant loss of top soil needed to sustain good plant growth. However, because of the lack of resources in most Mediterranean countries to replant areas destroyed by fire, the vast majority are left to re-seed themselves naturally. In many instances, this is either not successful or only partly so, thereby giving rise to a degraded landscape that may, with time, deteriorate to a desert-like condition. Timely and accurate information on the degree and extent of regeneration after a fire is, therefore, vital to assessing the potential for recovery of a burnt area and to initiating remedial measures, if necessary. To date, no studies have addressed these aspects in an integrated approach to the risk of land degradation following a forest fire. Those studies that have been done have concentrated on singular aspects of the problem, such as mapping the extent of burnt areas (Martin and Chuvieco, 1993; Barbosa and Gregorie 1995), the amount of recovery (Lopez-Garcia and Caselles, 1991; Viedma et al., 1995)), or the degree of soil erosion (Bocco et al., 1990; Shakesby et al., 1994).

At present, the main limitation of vegetation regrowth models is the difficulty in obtaining the necessary information on vegetation characteristics at the regional level, owing to the work-intensive manner in which vegetation parameters need to be measured. The use of satellite remote sensing data to map these parameters, such as vegetation type, density, and biomass, for input into vegetation regeneration models would overcome this shortcoming. These data and those on site conditions, including topography, geology, soil depth, land use, precipitation, and reoccurrence of fires, can be utilised as thematic or information layers within a GIS data base and operated upon by a set of decision rules based on expert knowledge of the main factors governing the potential for natural regeneration and risk of soil eroision, and hence the risk of desertification. For naturall regeneration potential, soil depth (moisture retention and root development) and aspect (amount of solar radiation received) are the most important factors, whereas for risk of soil erosion, surface geology (rock permeability), soil depth, and slope of the ground are the main determinants. Together, they provide an estimation of the risk of desertification.

3. STUDY AREA

Five fire-affected areas in Greece were used to establish the GIS data base and to develop the tools needed to transform and analyse the map, field, and remote sensing data acquired from them. The test areas are situated in the Pateras, Lavrio, Pendeli, and Barnabas regions of Attica, all of which comprise hilly to mountainous terrain. Ground data collection and the establishment of the expert rules used in the system were undertaken by the Institute of Mediterranean Forest Ecosystems at the National Agricultural Research Foundation (NARF) in Athens.

4. GROUND AND REMOTE SENSING DATA

Within the five test areas, information on vegetation, soil, geology, and physiography were collected from 39 reference sites, ranging in size from 1 ha to 4 ha, that represented different stages of plant regeneration after a forest fire. This information was used for establishing relationships between satellite data and ground features. In addition, 14 validation sites were selected for testing the accuracy of the system to map vegetation cover and to predict the potential for natural regeneration and risk of soil erosion and desertification.

Landsat Thematic Mapper (TM) data acquired from the summer of 1984, 1987, 1990, and 1993 formed the basis of the remote sensing data analysis. Each image was radiometrically calibrated (Price, 1987) and then corrected for atmospheric (Tarné et al, 1979; ONTAR, 1989) and topographic (Teillet et al., 1986) effects, before being geometrically rectified (geocoded), using an in-house developed software package (Joanneum Research, 1995).

5. THEMATIC INTERPRETATION

5.1 Vegetation Cover

A dense vegetation cover at a burnt site has normally re-established itself two to five years after a fire. However, the process of regeneration can be impeded by many factors, such as animal grazing, a paucity of precipitation, or soil erosion. The spectrally based Modified Soil Adjusted Vegetation Index (MSAVI) developed by Qi et al. (1994) and given by

$$\mathrm{MSAVI} = \frac{2 * \rho_{\mathrm{NIR}} + 1 - \sqrt{(2\rho_{\mathrm{NIR}} + 1)^2 - 8(\rho_{\mathrm{NIR}} - \rho_{\mathrm{RED}})}}{2}$$

where ρ_{NIR} = Reflectance in the NIR spectral region
ρ_{RED} = Reflectance in the red spectral region

was used to estimate the vegetation cover for the four Landsat TM image acquisition dates. For quantitative estimates of vegetation cover, field sites without and forested sites with full cover were used, in addition to the 39 reference sites comprising various levels of vegetation cover, to calibrate the algorithm.

Table 2 gives a comparison between the vegetation cover estimated in the field for the 14 validation sites and that derived by MSAVI.

Table 2 - Vegetation Cover for the Validation Sites.

Test Area	Site	Ground truth (%)	Estimate (%)	Residual (%)
Lavrio	1	85	82	3
	2	90	75	15
Pateras	1	75	74	1
	2	85	81	4
	3	70	86	16
	4	90	72	17
	5	30	43	13
	6	30	38	8
Pendeli-1	1	65	74	9
	2	70	92	22
	3	40	58	18
Pendeli-2	1	95	80	15
Varnavas	1	95	95	0
	2	100	91	9

5.2 Vegetation Cover Change

The change in vegetation cover at a burnt site over time provides an assessment of the degree of plant recovery after a fire. For the five test areas, the change in vegetation cover over the period 1984-1993 was determined by taking the difference in the MSAVI-derived vegetation cover values between the Landsat TM images from 1984 and 1987, 1987 and 1990, and 1990 and 1993. An example of this procedure is provided by the vegetation cover change maps produced for the Pendeli test area (Plate 1). Note the occurrence of new fires in the periods 1984-1987 and 1990-1993.

5.3 Potential for Natural Regeneration

The main restrictive factor for natural regeneration after a fire is the availability of water for plant regrowth in the dry period. In addition to the amount of rainfall, this depends on the water storage capacity of the soil and the topographic aspect of the site. Deep soils generally store more water and thereby carry denser vegetation than shallow soils, and south-facing slopes receive higher amounts of solar radiation than north-facing slopes and are therefore drier.

The water storage capacity of soils can be extracted from detailed soil maps, but, for most Mediterranean regions, such maps are not available. In such cases, satellite imagery can be used instead to indirectly derive the water storage capacity of a soil. In arid and semiarid regions, the amount of green biomass in the dry period is mainly dependent on the quantity of water available to the plants. Since there is a high correlation between MSAVI and green biomass or cover, MSAVI-derived values from TM imagery acquired in the dry period can be used to estimate the water storage capacity in wildland areas. However, this estimate is based on the assumption that the maximum possible biomass for a given soil is present, which is only the case when a forest has not been affected by fires for a long period of time. For the test areas in Attica, the maximum cover estimate was based on the maximum vegetation cover derived from TM scenes from 1984, 1987, 1990, and 1993, which were acquired in the dry season of the year.

To derive the potential for natural regeneration (PNR), the estimated water storage capacity of the soil is employed in combination with the terrain aspect of a site, using decision rules provided by the Institute of Mediterranean Forest Ecosystems (NARF) and given in Table 3. The aspect class is defined as 'south' for aspects from 135° to 315°, and otherwise as 'north'.

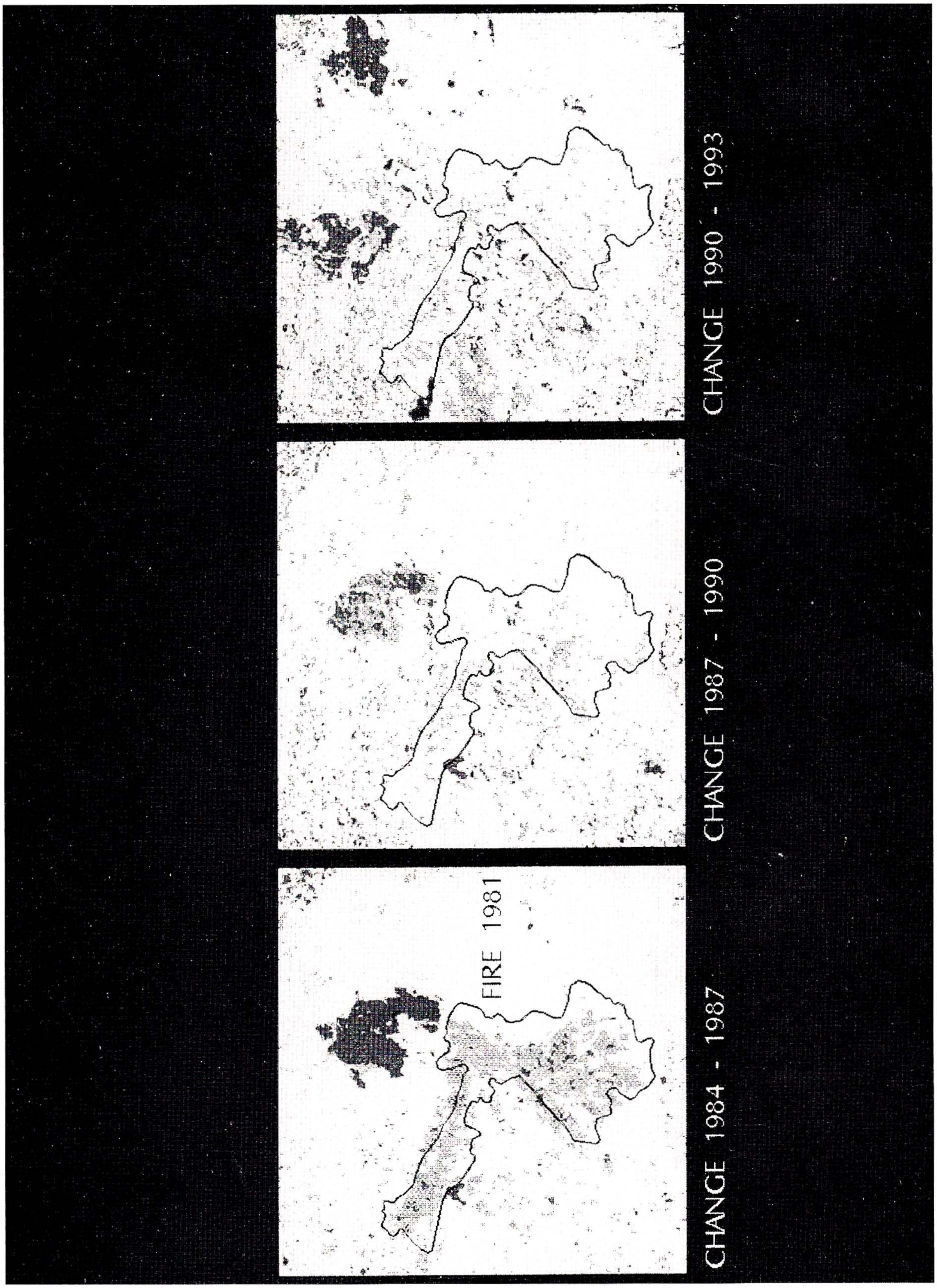

Figure 1 - Vegetation Couer change from 1984-1993 at the Pendeli Test Area. Note occurrences of New Fires (Red) in the Periods 1984-1987 and 1990-1993

See Plate VIII at end of volume

Table 3 - Potential for Natural Regeneration Decision Rules

Water Storage Capacity	Aspect Class	Potential for Natural Regeneration	
		Category	Characterisation
moderate to high	N	1	no limitation
	S	2	slight limitation
low	N	2	slight limitation
	S	3	moderate limitation
very low	N	4	strong limitation
	S	5	severe limitation

5.4 Risk of Soil Erosion

After a forest fire, the vegetation cover that protects the underlying soil substrate is removed, thus exposing the soil to the forces of wind and rain and thereby markedly increasing its ability to be denuded. The estimation of the risk of soil erosion (ROE), as defined by NARF, is governed by the following factors :

- Permeability (surface geology)
- Water storage capacity (soil depth)
- Topography (slope)

For an assessment of the risk of erosion, the above derived parameters for each map cell were combined in accordance to decision rules provided by NARF (Table 4). Surface geology was divided into two classes: permeable rocks (limestone, calcareous and siliceous Tertiary deposits, and colluvium) and impermeable rocks (metamorphic rocks) and obtained from digitised geological maps of the region. Because of the paucity of detailed soil depth data for the test areas, the maximum green vegetation cover (as described in section 5.3) for the summer periods between 1984 and 1993 was used, instead, to estimate water storage capacity. Similarly, the slope parameter proposed by NARF was replaced by the more comprehensive topographic factor LS, as defined by the Universal Soil Loss Equation and modified by Hensel (1991), which is related to watershed area characteristics

Table 4 - Risk of Soil Erosion Decision Rules

Permeability	Water Storage Capacity	Topographic Factor (LS)	Risk of Soil Erosion	
			Category	Characterisation
permeable	bare rocks	--	1	no risk
	low	< 1.5	2	slight risk
		> 1.5	3	moderate risk
	high	< 1.5	1	no to slight risk
		> 1.5	2	slight risk
impermeable	bare rocks	--	1	no risk
	low	< 1.5	4	high risk
		> 1.5	5	very high risk
	high	< 1.5	2	slight risk
		1.5 to 3	3	moderate risk
		> 3	4	high risk

5.5 Risk of Desertification

The risk of desertification (ROD) at a site increases the longer it remains without a protective vegetation cover after a fire and the higher its susceptibility to soil erosion is. Therefore, desertification risk can be assessed by combining the potential for natural regeneration (PNR) and the risk of soil erosion (ROE). According to NARF, the additive combination of these two factors gives the relative risk of desertification, which, for the five test areas, has been divided into five classes, with values ranging from a minimum of 2 (without any risk) for class 1, to a maximum of 10 (very high risk) for class 5.

Class Definitions for Risk of Desertification Assessment:

Class 1	(2)	:	Sites without any risk of desertification after a forest fire.
Class 2	(3,4)	:	Sites with a low risk of desertification after a forest fire.
Class 3	(5,6)	:	Sites with a moderate risk of desertification after a forest fire.
Class 4	(7,8)	:	Sites with a high risk of desertification after a forest fire.
Class 5	(9,10)	:	Sites with a very high risk of desertification after a forest fire.

6. EVALUATION OF RESULTS

A comparison between the results obtained by the remote sensing-GIS approach and those by field surveys carried out by forestry experts from NARF for the fourteen validation sites showed a 57% accuracy (± 10% of field survey values) was achieved in estimating vegetation density with the MSAVI algorithm, which increased to 93% when the variance was allowed to range between ± 20%. MSAVI attained a correlation value of 0.85 relative to the field data, with a RMS error of ± 13%.

Similarly, the predicted values for potential of natural regeneration were 43% for an exact agreement with the field values and 93% within ± 1 category, for risk of soil erosion, 57% and 93%, respectively, and for risk of desertification, 43% and 100%, respectively.

As the field surveys undertaken by NARF involved an estimation and not a measurement of the ground variables used in the analysis, a degree of unknown error is incorporated in the final results that represents the sum of errors from both the remote sensing-GIS and the field survey derived estimates.

7. CONCLUSIONS

Based on ground data from and knowledge of the study region provided by the National Agricultural Research Foundation, a Thematic Mapper based vegetation index algorithm was used to estimate the vegetation density and, in combination with map-derived determinants, to predict the potential for natural regeneration, risk of soil erosion, and risk of desertification for burnt areas in Greece. This information has been used to produce output maps at a scale of 1:50 000 that depict the different thematic categories, as have maps that show the change in vegetation cover over the period 1984-1993 in areas destroyed by fire. These latter maps indicate the rate of regrowth that is achievable after a fire under different physiographical conditions and can, therefore, be used as additional input in assessing the risk of erosion and desertification in affected areas.

The system, as now configured, is quasi-operational and can used to provide essential information to both forest and resources managers for assessing risk of desertification of forested areas immediately after a fire. After planned future refinements to the system are implemented, it is expected to become fully operational and thereafter made available to relevant organisations in the Mediterranean region.

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