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Agriculture, Ecosystems and Environment 105 (2005) 467–481
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Soil erosion as a driver of land-use change

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Received 7 October 2003; received in revised form 13 July 2004; accepted 14 July 2004

Abstract

Although much research has been carried out on the crop productivity response to soil erosion, little is known about the role of soil erosion as a driver of land-use change. Given, however, the some-times large erosion-induced reductions in crop yields, it appears likely that erosion has a strong impact on land-use. Abandonment of arable land due to declining productivity is a land-use change that may result from soil erosion. To test this hypothesis, the western part of Lesvos, Greece, was chosen as a case study area. Lesvos has experienced accelerated erosion on marginal soils over the last century during which important land-use changes have taken place. Of the 3211 ha that were under cereals in 1886, 53% (1711 ha) was converted to rangeland (only used for extensive grazing) by the mid-20th century. At the same time, however, cereals partly returned to neighbouring areas that were previously rangeland, implying that certain processes at the local scale resulted in land becoming unsuitable in one place and (relatively) more suitable in other places. In order to identify the relationship between these land-use changes and the occurrence of soil erosion, erosion was modelled backwards for the period 1886–1996 and soil depths reconstructed for the time when the land-use was assumed to have changed (the mid-1950s). A logistic regression was performed with soil depth, erosion and slope as explanatory variables and land-use change as the response variable. Abandonment/reallocation of cereals was found to be fairly well predicted by slope and soil depth. Path analysis showed erosion to be an important driver for the abandonment and reallocation of cereals, although next to slope and soil depth it has little additional predictive value. Based on the logistic model, it is anticipated that cereal cultivation in western Lesvos will probably be abandoned in the near future.

Keywords: Soil erosion; Crop productivity; Land abandonment; Land-use change; Logistic regression; Path analysis; Lesvos

1. Introduction

Many studies have reported on the detrimental effects of soil erosion on agricultural productivity. A review of data collected in intense, mechanised agricultural systems suggests that erosion reduces

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0167-8809/$ – see front matter
doi:10.1016/j.agee.2004.07.009

productivity on average by about 4% for each 10 cm of soil lost. Even higher reductions in productivity are possible although this depends on the contrast between top and subsoil properties (e.g. texture, fertility), and the stage of the erosion process. For soils with rooting depth restrictions (e.g. bedrock), productivity reductions become increasingly worse with incremental soil depth reductions (Bakker et al., 2004).

Although the negative effect of erosion on crop productivity has been extensively researched, little research has been carried out on the effect of erosion-induced reductions in crop productivity on land-use change (Marathianou et al., 2000; Van Rompaey et al., 2002). It may be hypothesised, however, that certain types of land-use change, such as the replacement of a land-use that puts high demands on soil by one with lower demands, are caused by soil erosion. As soil erosion is a process that varies strongly in space, one may then anticipate a migration of land-use types with high soil demands from strongly eroding sites to less eroding sites, if the latter are available.

In Lesvos (Greece), an island suffering from high erosion rates, important land-use change has occurred during the past century. Of the 4582 ha that were under cereals in 1886, 46% have been abandoned and are currently used for extensive grazing. In the western part of the island, where soils are shallower and the climate is more arid, this situation is even more pronounced. Here, a total of 3211 ha was under cereals in 1886, of which 53% (1711 ha) was abandoned (converted to rangeland) and 33% (1077 ha) changed into other land-uses. While cereal production was abandoned over large areas, other areas saw the introduction of cereal cultivation, bringing the total area under cereals in western Lesvos in 1996 back to 1822 ha, slightly more than half of the area in 1886. The new cereal areas were previously under rangeland (77%) and oak (*Quercus* spp.) plantations (16%). Only 13% (418 ha) of the area that was under cereals in 1886 is currently still under cereals (see maps in Marathianou et al., 2000).

Thus, besides a widespread abandonment of land under cereals, rangelands were also replaced by cereals at some locations. This suggests that exogenous economic factors were not the (primary) cause of cereal abandonment. If the cultivation of cereals were no longer economically viable, production would have been completely abandoned rather than being introduced in some areas. It seems reasonable to conclude that certain local scale processes were responsible for the abandonment of some areas of cereal cultivation making other areas relatively better suited for cereals, thereby causing a spatial shift in the location of production.

A socio-economic explanation may exist for the abandonment of cereals in the western hilly part of the island. In the second half of the 20th century, mechanised equipment was introduced and the former agricultural systems based on human and animal power were no longer able to compete (Kosmas et al., 1999). However, some sources claim that the abandonment of cereals was directly related to land degradation arising from soil erosion. Referring to Lesvos, Kosmas et al. (2000b) wrote: ‘‘as soil was eroded, land use usually shifted from agriculture to pasture due to increasingly poor yields from the various agricultural crops’’, and Marathianou et al. (2000) stated that land cultivated with cereals was greatly reduced in eroded, hilly areas where productivity was low.

When trying to assess the relationship between erosion and land-use change, a problem that is often encountered is that in general terms past agricultural productivity has increased rather than decreased because of the effects of technological innovations and improved land management. However, the analysis presented in this paper focuses on the spatial patterns of land-use change, rather than the temporal evolution of agricultural productivity. An investigation is made of the relationship between the spatial pattern of abandonment and reallocation and the severity of erosion during the period preceding a change in land-use.

A further problem is confounding between the effects of soil erosion and the direct effects of slope on land-use. In this case confounding is the result of a causal relationship between slope, erosion and soil depth. Slope can be seen as a driver of soil erosion, but also as a direct driver of land-use change because steeper slopes are more difficult to cultivate. Soil depth can, to a certain extent, be seen as the result of soil erosion. Soil erosion can affect abandonment in other ways: it affects soil depth, but it can also affect abandonment through the loss of nutrients and water-holding capacity.

The conceptual model presented in Fig. 1 summarises these interrelationships. Slope affects

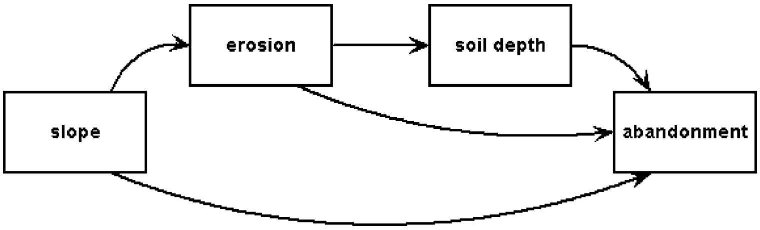

Fig. 1. Conceptual model where slope, erosion and soil depth affect abandonment.

abandonment in two ways: (1) via erosion and soil depth, and (2) directly. Erosion also affects abandonment in two ways: (1) through its effect on soil depth and (2) through its effect on other processes. In addition to reducing the soil depth, erosion degrades soil hydrologic conditions and decreases plant available water capacity. Sealing of the surface reduces the infiltration capacity of the soil, thereby reducing soil moisture. The resulting overland flow washes away nutrients and organic matter together with the fine, most fertile soil fraction and the water-holding capacity will decrease with increasing soil erosion. Thus, erosion leads to nutrient depletion, reduction in soil organic carbon and a negative alteration of the soil physical properties in terms of nutrient and water-holding capacity. Furthermore, erosion reduces soil biodiversity and soils become more vulnerable to diseases (Lal et al., 1999; Larson et al., 1985).

This paper attempts to identify the role of soil erosion as a driver of land-use change in an erosion-prone area by analysing the relation between soil erosion and abandonment of cereals in the western part of Lesvos. The hypothesis will be tested whether the land-use dynamics were driven by soil erosion. A path analysis will be carried out in order to evaluate the validity of the conceptual model presented in Fig. 1 and to assess the relative weights of the various arrows connecting slope, erosion, soil depth and the probability of land-use change.

2. Methodology

2.1. Study area

Lesvos is situated in the north-eastern part of the Aegean Sea and covers an area of 163,429 ha (Fig. 2). It is rather hilly with the highest peak 967 m above sea level. Steep slopes are dominant, covering 63% of the area. Soils are derived from a variety of parent materials such as igneous acid rock, ultrabasic rocks, metamorphic rocks, sedimentary deposits, unconsolidated deposits and recent alluvial deposits, and are classified as Typic Xerochrept, Lithic Xerochrept (Eurtric Cambisols) or Lithic Xerothent (Eutric Regosol) (Kosmas et al., 2000b). In the eastern, sub-humid region soil depths vary from 0.30 m to more than 1 m in depth, whereas in the dryer western part of Lesvos soils are generally shallow (0.15–0.30 m) to very shallow (0–0.15 m). Here, severely eroded soils are present with slopes greater than 12°, whereas slightly to moderately eroded soils are found in the sub-humid zone under the same slope classes (Kosmas et al., 2000a).

The climate is strongly seasonal with spatial variations in rainfall and high oscillations between minimum and maximum daily temperatures. Average annual rainfall is 670 mm, but there is a rainfall gradient of more than 45% from the east (sub-humid) to the west (semiarid). The average annual air temperature is 17.7 °C.

Two land-use periods have been identified (Kosmas et al., 1999). The first is called "the cereals and vines period" and the second one "the olives and pastures period". The mature stage of the second period began in the mid-20th century, when strong population migration (a nation-wide phenomenon between the mid-1950s to the late 1970s) depopulated the island (Kosmas et al., 1999).

Currently, the dominant land cover of western Lesvos is shrubland used for grazing (indicated as rangelands). There is some semi-natural oak forest, some olive groves and land cultivated with cereals (mainly wheat (*Triticum aestivum* L.) and oat (*Avena sativa* L.)) (Kosmas et al., 1999).

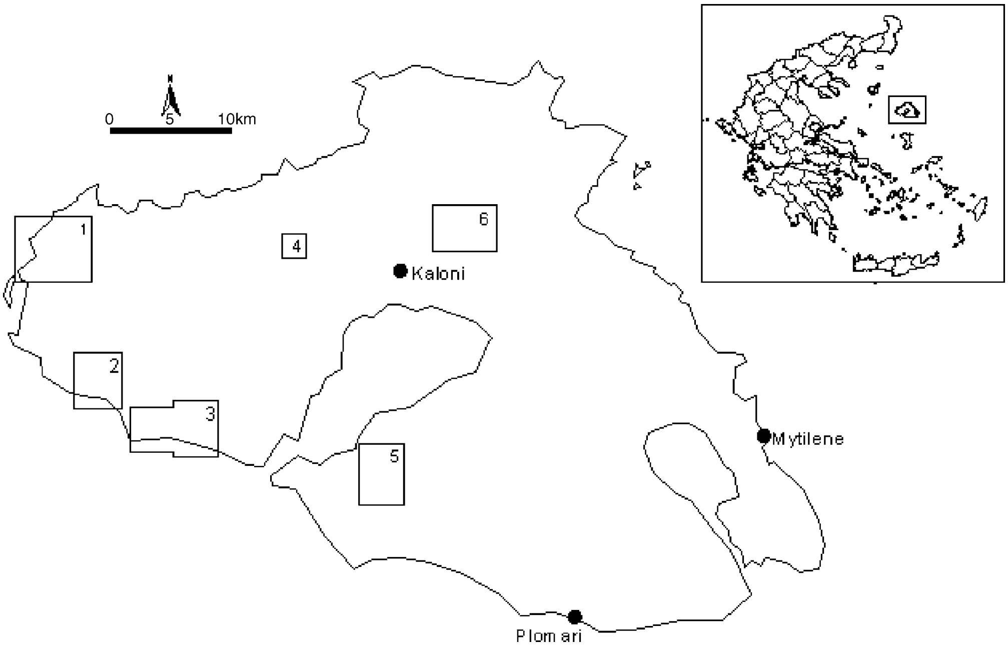

Fig. 2. The isle of Lesvos, with areas of interest (AoIs) depicted.

2.2. Methods

2.2.1. Land-use change

As the map of 1996 was made with the purpose of, amongst others, comparison with the 1886 map, both maps were based on surveys that used the same classification scheme (although the 1996 map contained a class tobacco, which did not exist in 1886), and both had the same scale (1:50,000) (Fig. 3). A difference in accuracy is likely to be the case, as the survey from 1886 was conducted using topographical maps, whereas the map from 1996 was made using topographical maps and aerial photographs. Furthermore, as each map was made by a different person, differences may exist due to subjective interpretations of the land-use of the different people. Although these factors may affect the exact delineation of boundaries between specific land-uses it is unlikely that they have had a significant effect on the mapped spatial distribution of the various land-uses as the difference between the land-use types that were distinguished are very clear-cut (Marathianou et al., 2000).

A visual comparison of both maps reveals that important land-use changes took place between 1886 and 1996. Most of this change occurred during the 1950s: according to the Statistical Service (Ministry of Agriculture), extensive migration of people to urban areas occurred during this decade due to, amongst other things, low land productivity, whilst in the same period the area cultivated with annuals largely decreased (Kosmas et al., 1999). For the analysis reported here, both land abandonment (i.e. the conversion of cereals to rangeland) and land reallocation (the conversion of rangeland to cereals) are assumed to have taken place in 1956. Clearly this is a simplification of the actual land-use history of the area, but the study did not intend to explain the actual timing of land-use change, rather its spatial distribution.

From the land-use change map, six smaller subsets were selected that comprised patches of land that were previously under cereals in 1886, and for which a part was converted to rangeland (abandonment) (Fig. 2). Three of these subsets also included a patch of land that was rangeland in 1886, of which a part was brought into cereal production in 1996 (reallocation). This allowed samples to be drawn from the various land-use change trajectories with similar sizes and which are, therefore, suitable for statistical tests.

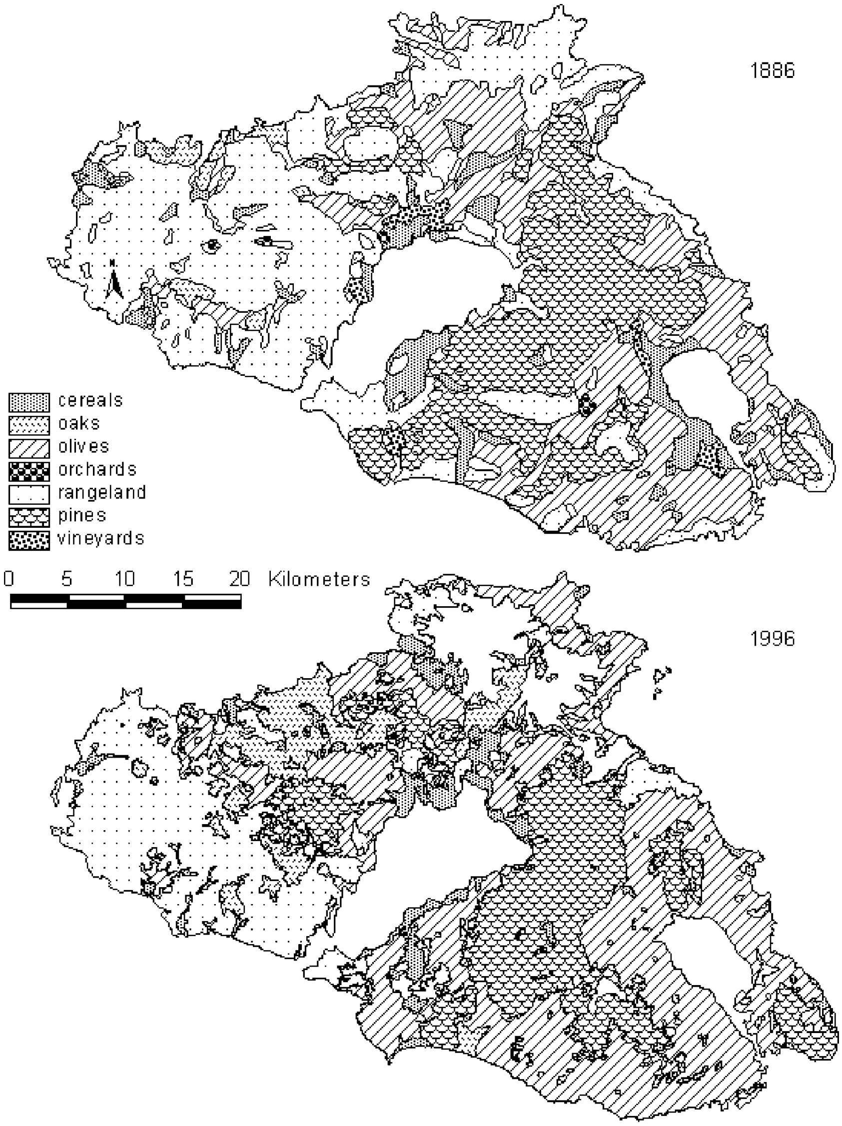

Fig. 3. Land-use in 1886 and in 1996 (Marathianou et al., 2000; Sifneou, 1996).

2.2.2. Reconstructing slope, erosion and soil depth

Erosion was modelled using the WATEM/SEDEM model, a spatially distributed model that simulates erosion and deposition by water and tillage processes in a two-dimensional landscape (Van Oost et al., 2000; Van Rompaey et al., 2002). WATEM/SEDEM allows the integration of landscape structure or the spatial organisation of different land units and the connectivity between them. In order to avoid problems with respect to the spatial variability of parameter values and the inherent uncertainty of these parameter estimates, WATEM/SEDEM is a relatively simple, steady-state, topography-driven model. The water component of WATEM/SEDEM uses an adapted version of the revised universal soil loss equation (RUSLE). The tillage component of WATEM/SEDEM uses a diffusion-type equation for which the intensity of the tillage process is described by a single parameter (the tillage transport coefficient or *ktil*-value).

WATEM/SEDEM was initially designed to predict erosion into the future, but has been modified in this study to calculate erosion into the past. This was done by calculating ''forward'' erosion for 1 year, reversing the sign of the calculated erosion and deposition values and modifying the digital terrain model accordingly. This procedure was then repeated for the required number of years.

Maps were produced with USLE *C*- and *K*-factor values based on soil and vegetation data. The *R*-factor was assumed to be constant for the western part of the island and was set to 0.041 MJ mm h^{-1} m^{-2} per year (Roose, 1996). The *P*-factor was calculated taking into account contour ploughing for cereal cultivation for the second half of the century (0.6 for slopes of 0–2°, 0.5 for slopes of 2–6°, 0.65 for slopes of 6–18° and 0.85 for slopes of 18–25°). The LS factor was calculated according to the algorithm of Govers (1991). Together with a digital terrain model (derived from interpolation of digitised contour lines, Stuckens, 2003), these data layers served as input for the WATEM/SEDEM model. The tillage transport coefficient was estimated as 300 kg m^{-1} for the second half of the century, and 200 kg m^{-1} for the first half of the century (based on data from Van Muysen et al., 2000). These values assume that fields were ploughed once a year with a mouldboard plough, to an average depth of 0.20 m during the first half of the century and 0.25 m during the second half of the century. During the first half of the century, ploughing speeds were less than 2 km h^{-1}, but exceeded 2 km h^{-1} in the second half of the century.

WATEM/SEDEM was used to reconstruct soil depths and slope for 1956, the assumed moment of land-use change, and for 1886, based on the soil (depth) map for 1996 (Kosmas et al., 2000a). Erosion was calculated for the period 1886–1956 in metre of soil loss. For subsequent statistical analyses, data points were randomly sampled from these maps (slope and soil depth in 1956, erosion during the period 1886–1956) with an average density of one point per ha. This was done to avoid dependency between observations of land-use change. Land-use decisions in the study area are usually made for individual field parcels which are smaller than 1 ha.

2.2.3. Logistic regression

A dichotomous logistic regression analysis was carried out to identify the extent to which abandonment and reallocation of cereals has been driven by slope, soil depth and erosion. Dichotomous logistic regression is a regression technique applicable when the response variable (in this case, land-use change) takes only one of two possible values (change or no change). The logistic model describes the expected value of the land-use change (i.e. *E*(change)), or the probability of land-use change, in terms of the following 'logistic' formula:

$$E(\text{change}) = \frac{1}{1+\exp\left[-\left(\beta_0+\sum_{j=1}^{k}\beta_j X_j\right)\right]} = \Pr(\text{change}) \quad (1)$$

Thus, the probability of land-use change is a function of *k* explanatory variables *X* (in this case slope, erosion and/or soil depth).

An alternative way to formulate the logistic model is the logit form. The logit is a transformation of the probability Pr(change) that is used to make the model linear and is defined as follows (Kleinbaum et al., 1998):

$$\text{logit}[\Pr(\text{change})] = \log_e\left[\frac{\Pr(\text{change})}{\Pr(\text{no change})}\right] = \beta_0+\sum_{j=1}^{k}\beta_j X_j \quad (2)$$

Using the SAS software (SAS Institute, Inc., 2001), the models in Table 1 were tested.

2.2.4. Path analysis

In order to validate the conceptual model presented in Section 1 and to assign a weight to the various arrows (see Fig. 1), a path analysis was performed. Path analysis is a technique – more commonly used in social sciences – that identifies the individual contribution of each explanatory variable to the model fit based on correlation coefficients (a measure of overlap). Traditional path analysis, however, is not applicable to logistic regression (Davis, 1985). Instead, likelihood-ratio χ^2-values are calculated. Mathematically, likelihood-ratio χ^2-values have additive properties, provided that there is no correlation

Table 1
Models tested using logistic regression, which relate slope, erosion and soil depth to abandonment (a) and reallocation (r), respectively

Model	Model ID
logit[Pr(abandonment)] = $\beta_0 + \beta_1$ (slope)	1a
logit[Pr(abandonment)] = $\beta_0 + \beta_1$ (erosion)	2a
logit[Pr(abandonment)] = $\beta_0 + \beta_1$ (soil depth)	3a
logit[Pr(abandonment)] = $\beta_0 + \beta_1$ (slope) + β_2 (erosion)	4a
logit[Pr(abandonment)] = $\beta_0 + \beta_1$ (slope) + β_2 (soil depth)	5a
logit[Pr(abandonment)] = $\beta_0 + \beta_1$ (erosion) + β_3 (soil depth)	6a
logit[Pr(abandonment)] = $\beta_0 + \beta_1$ (slope) + β_2 (erosion) + β_3 (soil depth)	7a
logit[Pr(reallocation)] = $\beta_0 + \beta_1$ (slope)	1r
logit[Pr(reallocation)] = $\beta_0 + \beta_1$ (erosion)	2r
logit[Pr(reallocation)] = $\beta_0 + \beta_1$ (soil depth)	3r
logit[Pr(reallocation)] = $\beta_0 + \beta_1$ (slope) + β_2 (erosion)	4r
logit[Pr(reallocation)] = $\beta_0 + \beta_1$ (slope) + β_2 (soil depth)	5r
logit[Pr(reallocation)] = $\beta_0 + \beta_1$ (erosion) + β_3 (soil depth)	6r
logit[Pr(reallocation)] = $\beta_0 + \beta_1$ (slope) + β_2 (erosion) + β_3 (soil depth)	7r

between the independent variables (Lemay, 1999). Where explanatory variables are completely independent, the overall explanatory value of the model comprises the explanatory values of the explanatory variables, so that the overall model χ^2 is equal to the sum of the χ^2 of the individual independent variables:

$$\chi^2 \operatorname{var} ABC = \chi^2 \operatorname{var} A + \chi^2 \operatorname{var} B + \chi^2 \operatorname{var} C \tag{3}$$

When explanatory variables are correlated, the predictive value of the variables will 'overlap' and the sum of the χ^2-values of the explanatory variables will therefore be larger than the χ^2-value of the overall model. Therefore, this measure can be used to determine the extent of overlapping and to evaluate models that attempt to exclude the confounding of variables (Hamel et al., 1999).

The conceptual model presented in Fig. 1 implies confounding between slope and erosion and between erosion and soil depth. If all χ^2-values were added, the impact of slope would in part be double-counted: once in the χ^2-value of slope, and secondly in the χ^2-value of erosion. This problem can be solved by decomposing the explanatory value of slope into a part that directly affects abandonment ($a_1\chi^2_{\text{slope}}$) and a part that affects abandonment through erosion ($a_2\chi^2_{\text{slope}}$). Likewise the explanatory value of erosion can be decomposed into a part that directly affects abandonment ($a_4\chi^2_{\text{erosion}}$) and a part that affects abandonment through soil depth ($a_3\chi^2_{\text{erosion}}$) (Fig. 4). In order to find out how much slope and erosion contribute to each pathway, the individual and common χ^2-values of the applicable combinations of explanatory variables will be assigned to the various pathways.

It is important to note that the analysis presented here only allows investigation of the extent to which the data support the proposed hypothesis: as all relationships are statistical in nature no causality can be proven. Path analysis merely illuminates which of two or more competing models, derived from theory, is most consistent with the pattern of correlations found in the data (Garson, 2003).

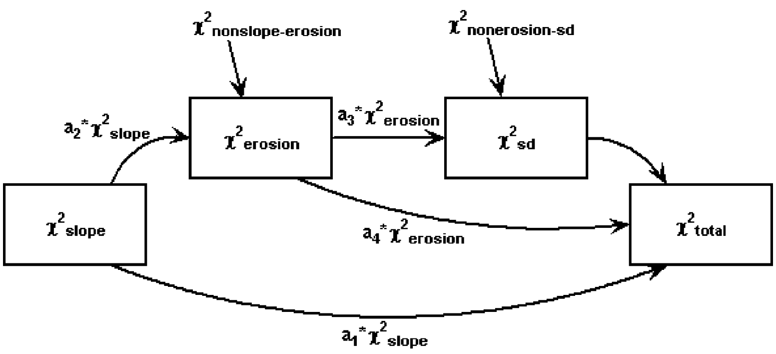

Fig. 4. Conceptual model with χ^2 indicated.

Table 2
The physical characteristics of each area of interest (AoI) through time for abandoned land, land still under cereals, reallocated land and land under permanent rangeland

AoI	Change	Surface (ha)	Slope 1956 (°)	Soil loss 1886–1956 (m)	Soil depth 1886 (m)	Soil depth 1956 (m)	Soil depth 1996 (m)
1	Abandoned	576	8.0a	0.26 a	0.71a	0.45a	0.26 a
	Still cereals	159	2.9 b	0.10 b	1.16 b	1.06 b	0.95 b
	Reallocated	126	2.8 a	0.07 a	1.31 a	1.24 a	1.13 a
	Permanent rangeland	1362	10.1 b	0.31 b	0.70 b	0.39 b	0.16 b
2	Abandoned	206	6.9 a	0.22 a	1.32 a	1.10 a	1.01 a
	Still cereals	65	1.7 b	0.09 b	1.85 b	1.76 b	1.75 b
3	Abandoned	185	9.2 a	0.40 a	1.34 a	0.94 a	0.80 a
	Still cereals	46	1.3 b	−0.02 b	1.64 b	1.66 b	1.61 b
	Reallocated	152	3.0 a	0.08 a	1.68 a	1.60 a	1.56 a
	Permanent rangeland	600	8.1 b	0.21 b	0.75 b	0.54 b	0.44 b
4	Abandoned	46	14.6 a	0.41 a	1.60 a	1.19 a	1.12 a
	Still cereals	26	3.6 b	0.05 b	1.37 b	1.32 b	1.25 b
5	Abandoned	78	2.3 a	0.03 a	0.61 a	0.58 a	0.56 a
	Still cereals	386	1.9 b	0.04 a	1.00 b	0.96 b	0.94 b
	Reallocated	154	0.9 a	0.01 a	0.96 a	0.95 a	0.93 a
	Permanent rangeland	225	2.1 b	0.04 b	0.49 b	0.45 b	0.44 b
6	Abandoned	62	6.9 a	0.16 a	1.33 a	1.17 a	1.12 a
	Still cereals	158	1.3 b	0.03 b	1.52 b	1.49 b	1.46 b

AoI: area of interest (see also Fig. 2). Values not followed by the same character are significantly different at the 0.05 interval.

3. Results

3.1. Erosion, soil depth and slope characteristics per land-use change trajectory

Table 2 summarises the characteristics of the six areas of interest (AoIs). For areas that were under cereals, estimated soil losses in the period 1886–1956 ranged from 0.05 m for non-erosion-prone land to 0.26 m for erosion-prone land. This is consistent with the findings of Tsara et al. (2001), who found soil losses of 0.24–0.30 m in a 63-year period for a similar erosion-prone area in Greece.

For all AoIs, soil loss during the period 1886–1956 is more severe in areas that were abandoned compared to neighbouring areas that remained under cereals. The abandoned areas are also located on steeper slopes, and the soil depths were often very marginal for cereal cultivation at the assumed moment of change. Likewise, the areas taken into cultivation suffered less erosion during the period 1886–1956 than surrounding areas that remained under rangeland. Furthermore, slope and soil depth values were more favourable in the areas taken into cultivation compared to surrounding areas.

In Table 3, the values of slope, soil loss and soil depth are shown for all the AoIs. All values

Table 3
The average physical characteristics through time for abandoned land, land still under cereals, reallocated land and land under permanent rangeland

Change	Surface (ha)	Slope 1956 (°)	Soil loss 1886–1956 (m)	Soil depth 1886 (m)	Soil depth 1956 (m)	Soil depth 1996 (m)
Abandoned	1153	7.8	0.26	0.98	0.72	0.55
Still cereals	840	2.0	0.05	1.24	1.19	1.15
Reallocated	432	2.2	0.06	1.32	1.26	1.21
Permanent rangeland	3287	8.6	0.29	0.71	0.42	0.18

Table 4
Likelihood-ratio χ^2-values for all tested models, for abandonment of cereals

Model ID	Deviation from						
	Intersect only	1a	2a	3a	4a	5a	6a
1a	$698.233^{***(1)}$	0					
2a	$292.912^{***(1)}$	$-405.321^{***(1)}$	0				
3a	$292.194^{***(1)}$	$-406.039^{***(1)}$	$-0.718^{(1)}$	0			
4a	$703.062^{***(2)}$	$4.829^{*(1)}$	$410.15^{***(1)}$	$410.868^{***(2)}$	0		
5a	$803.639^{***(2)}$	$105.406^{***(1)}$	$510.727^{***(2)}$	$511.445^{***(1)}$	$100.577^{***(1)}$	0	
6a	$493.051^{***(2)}$	$-205.182^{***(2)}$	$200.139^{***(1)}$	$200.857^{***(1)}$	$-210.011^{***(1)}$	$-310.588^{***(1)}$	0
7a	$806.843^{***(3)}$	$108.61^{***(2)}$	$513.931^{***(2)}$	$514.649^{***(2)}$	$103.781^{***(1)}$	$3.204^{(1)}$	$313.792^{***(1)}$

Columns showing 'deviation from intersect only ... 6a'' contain the differences in $-2 \log L$ values, or likelihood-ratio χ^2-values between the various models (Table 1) (including the intersect only). The significance of these differences are tested as χ^2-values, whereby the degrees of freedom are determined by the number of additional variables included in the model (when two models were compared that each had one variable, this was regarded as comparing a one-variable model with an intersect-only model and, therefore, tested as χ^2 with one degree of freedom) (Kleinbaum et al., 1998); number between brackets: degrees of freedom. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

between abandoned and still cereals and between reallocated and permanent rangeland are significantly different with a probability of more than 99.999%.

3.2. Logistic regression

Tables 4 and 5 give the goodness of fit of the tested models (see Table 1) compared to the absence of a model (intersect only) and to the other models, for abandonment and reallocation, respectively.

For the abandonment of cereals, only model 7a does not differ significantly from model 5a, meaning that the variable erosion has no significant added value to a model already containing soil depth and slope. The same is true for models 7r and 5r describing the reallocation of cereals.

The optimal model for the prediction of abandonment is given by

$$\text{logit}[\Pr(\text{abandonment})] = -0.075 + 0.3357 \times \text{slope} - 0.9226 \times \text{soil depth} \quad (4)$$

The erosion term is not included since the added predictive value of this variable is much lower than its uncertainties: analysis showed that the uncertainty of the logit is much higher when erosion is included, whereas the added value as a predictor is quite low. The added value of slope and soil depth as predictors is much higher than the uncertainty involved. Furthermore, the high correlation of erosion with slope causes unreliable coefficient estimates (Kleinbaum et al., 1998).

Table 5
Likelihood-ratio χ^2-values for all tested models, for reallocation of cereals

Model ID	Deviation from						
	Intersect only	1r	2r	3r	4r	5r	6r
1r	$533.943^{***(1)}$	0					
2r	$63.266^{***(1)}$	$-470.677^{***(1)}$	0				
3r	$770.713^{***(1)}$	$236.77^{***(1)}$	$707.447^{***(1)}$	0			
4r	$537.814^{***(2)}$	$3.871^{*(1)}$	$474.548^{***(1)}$	$-232.899^{***(2)}$	0		
5r	$959.306^{***(2)}$	$425.363^{***(1)}$	$896.04^{***(2)}$	$188.593^{***(1)}$	$421.492^{***(1)}$	0	
6r	$795.977^{***(2)}$	$262.034^{***(2)}$	$732.711^{***(1)}$	$25.264^{***(1)}$	$258.163^{***(1)}$	$-163.329^{***(1)}$	0
7r	$960.356^{***(3)}$	$426.413^{***(2)}$	$897.09^{***(2)}$	$189.643^{***(2)}$	$422.542^{***(1)}$	$1.050^{(1)}$	$164.379^{***(1)}$

Number between brackets: degrees of freedom.
$^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

For this model 83.8% of the pairs are concordant. If it is assumed that the threshold between the probability of abandonment and the probability of no abandonment is 0.5 (meaning that when the probability is higher than 0.5 there will be abandonment, and if lower than 0.5 there will be no abandonment), the model explains 75.6% of the observed abandonment.

The optimal model for the prediction of reallocation is

$$\text{logit}[\Pr(\text{reallocation})] = -2.0695 - 0.2332 \times \text{slope} + 2.0517 \times \text{soil depth} \quad (5)$$

For this model, 90.2% of the pairs are concordant and again, assuming the threshold in probability of, respectively, reallocation and no reallocation is 0.5, the model explains 82.0% of the observed reallocation.

3.3. Path analysis

Following the scheme of Fig. 4 (based on the conceptual model in Fig. 1), the following set of equations apply (provided the model excludes confounding):

$$\chi^2_{\text{erosion}} = a_2\chi^2_{\text{slope}} + \chi^2_{\text{non-slope-erosion}} = a_3\chi^2_{\text{erosion}} + a_4\chi^2_{\text{erosion}} \quad (6)$$

$$\chi^2_{\text{sd}} = a_3\chi^2_{\text{erosion}} + \chi^2_{\text{non-erosion-sd}} \quad (7)$$

$$a_1\chi^2_{\text{slope}} + a_2\chi^2_{\text{slope}} = \chi^2_{\text{slope}} \quad (8)$$

$$\chi^2_{\text{total}} = a_1\chi^2_{\text{slope}} + a_4\chi^2_{\text{erosion}} + a_3\chi^2_{\text{erosion}} + \chi^2_{\text{non-erosion-sd}} \quad (9)$$

The χ^2-values for 'non-slope-erosion' and 'non-erosion-soil depth' are the added values of, respectively, erosion and soil depth, compared to a model having, respectively, only slope and erosion as explanatory variables, i.e., the difference between the goodness of fit of the model with only slope and the model with slope and erosion, and the difference between the goodness of fit of the model with only erosion and the model with erosion and soil depth.

The following χ^2-values are known from the logistic analysis (Table 4):

$$\chi^2_{\text{erosion}} = 292.912$$

$$\chi^2_{\text{soil depth}} = 292.194$$

$$\chi^2_{\text{non-slope-erosion}} = 4.829$$

$$\chi^2_{\text{non-erosion-sd}} = 200.139$$

Thus,

$$a_2\chi^2_{\text{slope}} = \chi^2_{\text{erosion}} - \chi^2_{\text{non-slope-erosion}} = 292.912 - 4.829 = 288.083$$

$$a_1\chi^2_{\text{slope}} = \chi^2_{\text{slope}} - a_2\chi^2_{\text{slope}} = 698.233 - 288.083 = 410.150$$

$$a_3\chi^2_{\text{erosion}} = \chi^2_{\text{soil depth}} - \chi^2_{\text{non-erosion-sd}} = 292.194 - 200.139 = 92.055$$

$$a_4\chi^2_{\text{erosion}} = \chi^2_{\text{erosion}} - a_3\chi^2_{\text{erosion}} = 292.912 - 92.055 = 200.857$$

Completing Eq. (9) with these numbers gives (Fig. 5):

$$\chi^2_{\text{total}} = 410.150 + 200.857 + 92.055 + 200.139 = 903.201$$

4. Discussion

4.1. Identifying the effect of erosion on land-use change

It appears that the abandonment and the reallocation of cereals are strongly related to certain physical properties of the sites. Statistically, the abandonment and reallocation of cereals are well predicted with slope and soil depth as explanatory variables. Erosion has, next to slope and soil depth, no significant added value in predicting abandonment and reallocation. The conceptual model (Fig. 1) provides a possible explanation of why the predictive value of erosion is not found to be significant. Erosion is in the middle of a 'chain of drivers' and, therefore, when both slope and soil depth are included as predictors, erosion itself

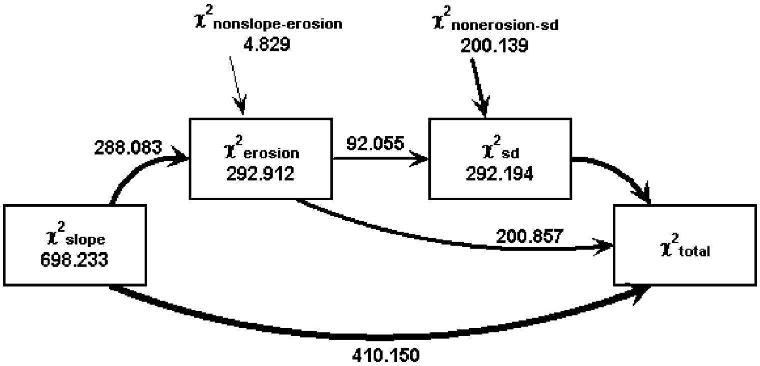

Fig. 5. χ^2-Value contributions of all explanatory variables.

has no added value as a predictor: the potential effect of erosion on land-use change is already included in the variables soil depth and slope.

Slope has significant added value as a predictor compared to erosion. The path analysis showed that the total impact of slope was divided approximately into a third via erosion and soil depth and two-thirds directly. It appears likely, therefore, that slope affects abandonment in ways other than through erosion (e.g. the introduction of machinery that was unsuitable for steep slopes). Likewise, the effect of erosion on abandonment can be divided approximately into one-third via soil depth and two-thirds directly. Erosion affects, therefore, land-use change not only through the reduction in soil depth (and therefore rooting depth and plant available water), but also through the removal of organic matter and nutrients from the soil, loss of soil structure and water-holding capacity and increased stoniness due to selective removal of fine soil particles (Gonzalez-Hidalgo et al., 1999; Lal et al., 1999; Larson et al., 1985). Especially in Lesvos, where the water-holding capacity generally is low (13.1–14.8 mm of water per 10 cm of soil, Kosmas et al., 2000a) and where stoniness of the soils is problematic for the workability, it is not surprising that these 'direct' effects of erosion play a significant role.

It is possible that differences between the maps could have derived from differences in the survey methods. This could influence the outcomes of the regression analysis. Such differences, however, are more likely to decrease the strength of the statistical relationship because they would introduce random noise rather than creating a structured, spatial pattern that relates to erosion.

4.2. Improving the conceptual model

If the conceptual model in Fig. 1 was a good representation of reality and accounted for all confounding between variables, the sum of the χ^2-values of the components (903.201) would equal the χ^2-value of the total model. However, this is not the case as the overall χ^2-value of the total model is 806.043 (Table 4). Thus, not all confounding is excluded.

It is interesting to explore, therefore, a conceptual model where slope not only affects soil depth via erosion, but also directly (see Fig. 6). This could occur

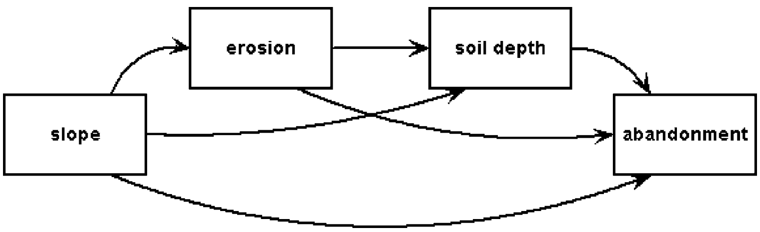

Fig. 6. Revised conceptual model.

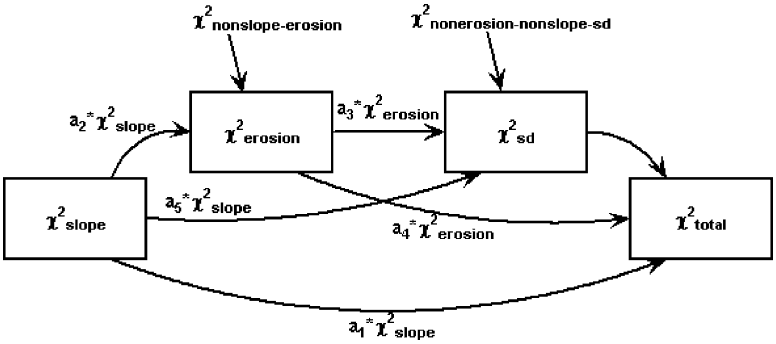

Fig. 7. Revised conceptual model with χ^2 indicated.

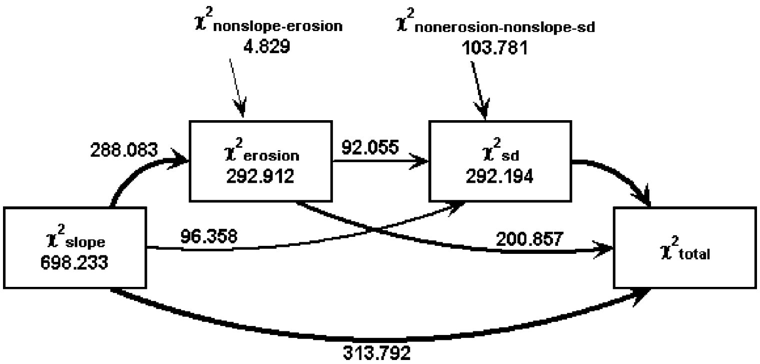

Fig. 8. Revised conceptual model with χ^2-value contributions of all explanatory variables.

because of: (a) pedogenesis (soil development may be slower on steep slopes), and/or (b) geomorphology (long-term erosion rates are related to slope gradient, leading to a relationship between slope gradient and soil depth, prior even to the use of land for agriculture). This long-term erosion effect was not captured by the WATEM/SEDEM model used here to estimate erosion rates between 1886 and 1956. Contrary to long-term erosion rates, erosion rates between 1886 and 1956 are strongly affected by land-use.

The χ^2-values associated with the different pathways depicted in Fig. 6 can then be calculated as above

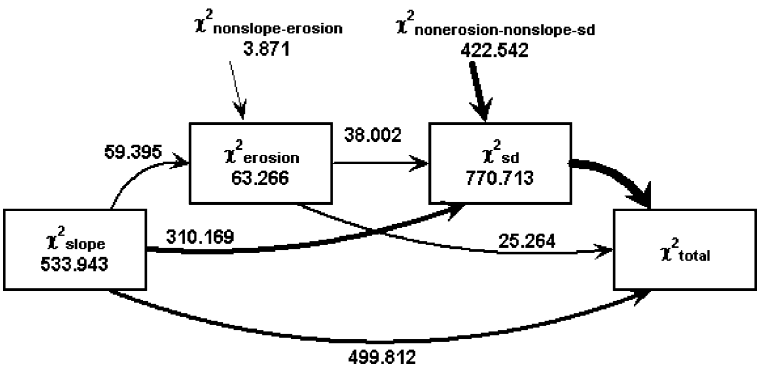

Fig. 9. Conceptual model for reallocation of cereals with χ^2-value contributions of all explanatory variables.

(Fig. 7). The sum of the individual model components is now (Fig. 8):

$$\chi^2_{\text{total}} = 313.792 + 200.857 + 92.055 + 103.781 + 96.358 = 806.843$$

This value is very close to the χ^2-value of the overall model (806.04) and, therefore, it can be assumed that the model excludes most of the significant confounding.

It seems that a significant part of the explanatory power of the model can be attributed to the erosion/soil depth path, although the improved model does show a relatively strong, direct linkage between slope and soil depth. This implies that even if not

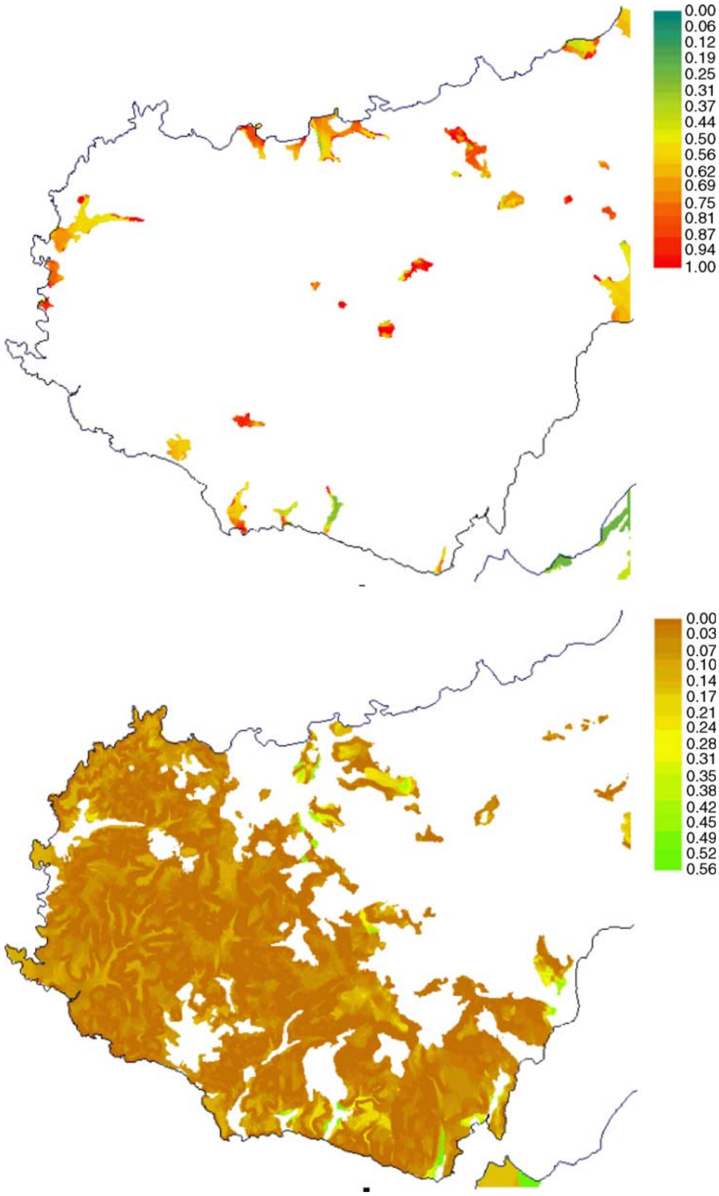

Fig. 10. Change-probability maps derived from logistic regression: (a) probability of rangeland being reallocated to cereal cultivation; (b) probability of abandonment of areas currently under cereals.

accelerated by human-induced erosion, soil depths would still be related to a certain extent to slope. The role of erosion as a driver for land-use change is thus slightly reduced by this finding.

When the same steps are repeated for the reallocation model (Fig. 9), the contribution of the separate χ^2-values is as follows:

$$\chi^2_{\text{total}} = 0.31 \times 533.943 + 0.40 \times 63.266 + 0.60 \times 63.266 + 422.542 = 960.356$$

The sum of the components is exactly the same as the χ^2-value of the total model, so the model excludes confounding.

The model explains 82.0% of the observed reallocation. Although the erosion/soil depth path contributes significantly to the reallocation model, it is much less important than in the abandonment model. Slope itself once more plays a considerable role. It appears that for the reallocation of cereals, soil depth has a higher predictive value, relative to slope, compared to that for the abandonment of cereals. This implies that in the process of decision-making, farmers were more concerned with soil depth than with slope. This is understandable assuming that decisions were based on farmers' experience with the abandonment of cereals: marginal productivity is more easily associated with shallow soils than with steep slopes, which are indirectly related to decreasing productivity. Furthermore, on shallow soils the effects of erosion on productivity manifest themselves more strongly as in shallow soils nutrient and water availability is lower. Therefore, a further reduction due to erosion results in a greater relative loss on shallow soils than on deeper soils.

Furthermore, the path from slope to soil depth is much stronger for reallocation than for abandonment. Soil depths on rangeland are much less affected by recent, human-induced soil erosion. Consequently, erosion is still strongly associated with slope gradient, due to the effect of slope gradient on soil formation and on long-term erosion rates.

4.3. Future perspectives

Fig. 10a and b shows the probability of abandonment of areas currently under cereals, and the probability of rangeland being reallocated to cereals based on the models derived from the logistic regression. The probability of abandonment of cereals is higher than 0.5 almost everywhere, whereas the probability of reallocation of rangelands to cereals is almost always lower than 0.5. This implies that under current conditions almost all fields currently under cereals will eventually become abandoned since the current rangelands have no potential for cereal cultivation. Sustainable cereal cultivation may be possible in small patches of deep soil that are not evident because of the resolution of the soil map, but these patches will be rare.

5. Conclusions

Statistical analysis indicates that the physical characteristics of the landscape have been important factors in the abandonment and subsequent reallocation of land under cereals: land with high slope gradients, high erosion rates and shallow soils tended to be taken out of cereal production, while new arable land for cereals is mainly located in areas with deep soils, low erosion rates and with relatively low slope gradients.

The strong relationship between abandonment and soil depth indicates that erosion (i.e. the decrease in soil depth) may be responsible for abandonment. Based on the results of the logistic regression, the goodness of fit of the logistic abandonment model was attributed as follows: ca. 25% to the direct impact of erosion, ca. 36% to the erosion/soil depth path and ca. 39% to the direct impact of slope.

For the reallocation, the contribution of the direct impact of slope to the goodness of fit of the model was much less (ca. 17%) while the effect of slope through the erosion/soil depth path was much more important (ca. 80%). This can be explained by the fact that farmers associated the marginal productivity of the land they had abandoned previously more to the shallowness of the soils than to steep slopes. Consequently, soil depth was a more important criterion when selecting land for reallocation than slope gradient.

The results of the analysis presented here are consistent with the hypothesis that, in the case of west Lesvos, the spatial pattern of land-use change is significantly affected by erosion, despite the fact that logistic regression did not identify modelled erosion rates as a significant independent variable due to confounding effects. This illustrates the problem that traditional statistical analyses may be unable to identify significant drivers of land-use change. Furthermore, the results suggest that soil erosion risk should be included as a variable in more mechanistic land-use change models (e.g. Rounsevell et al., 2002) at least when areas with marginal soils are studied.

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