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The response of soil erosion and sediment export to land-use change in four areas of Europe: The importance of landscape pattern

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Abstract

The response of erosion and sediment export to past land-use change has been studied in four agricultural areas of Europe. Three of these areas were subject to land abandonment or de-intensification and one to intensification of land-use practices. Erosion and sediment yield were modeled using the WaTEM/SEDEM model, which combines the RUSLE equation with a sediment routing algorithm. Spatial relationships between the RUSLE *C*-factor (i.e. land-use) and other erosion and sediment export-determining factors (slope, soil erodibility and distance to rivers) were investigated, as these account for non-linearity in the response of erosion and sediment export to land-use change.

Erosion and sediment export have decreased enormously in the de-intensified areas, but slightly increased in the intensively cultivated area. The spatial pattern of land-use change in relation to other erosion and sediment export-determining factors appears to have a large impact on the response of soil erosion and sediment export to land-use change. That the drivers of abandonment of arable land and erosion coincide indicates that de-intensification leads to a more favourable landscape pattern with respect to reduction of erosion and sediment export. This mechanism applies not only within the study areas, but also among the European study areas where the process of intensification of some areas and de-intensification of others might result in an overall decrease of erosion and sediment yield through time.

Keywords: Soil erosion; Land-use change; Europe; Landscape pattern

1. Introduction

Land-use change in Europe over the past decades has largely been driven by the introduction of new technologies (for a discussion see Ewert et al., 2005). The introduction of mechanized equipment, artificial fertilisers, herbicides, pesticides and new cultivars has led to an increase in productivity of between 400 and 500% (Hafner, 2003; Bakker et al., 2005a) depending on the crop type. Consequently, intensification has occurred in areas that were suitable for the implementation of these new technologies, and abandonment or de-intensification

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(i.e. decreasing agricultural production by reducing aggregate input levels per unit area) has occurred in areas that were less suitable (Mather et al., 1999; MacDonald et al., 2000; Baldock et al., 2002).

Whether or not an area is suitable or not for the application of new technologies is largely determined by accessibility, the potential of available soil resources, and the workability of the fields (i.e. slope, stoniness, etc.). Because of this, hilly and mountainous areas, especially those with degraded soils, have often experienced de-intensification whereas intensification has occurred on flatter areas with deep fertile soils.

De-intensification of land-use often implies the regeneration of natural land cover, or a conversion from a low protection cover type (e.g. arable land) to a higher protection cover type (e.g. grassland or forest). De-intensification of land-use may therefore be beneficial with respect to a reduction in onsite soil erosion and sediment export to rivers and lakes (Vanacker et al., 2005). Soil erosion and sediment export to rivers and lakes are commensurate with the cultivation of arable land and, depending on climate, on intensive grazing, especially in sloping areas. Soil erosion is to a large extent determined by the absence of protective land cover, whereas sediment export to rivers and lakes is determined by onsite sediment production and the connectivity of sediment sources and the river or lake. The latter factor is also a function of land-use, as the sediment transport capacity is different for different types of land-use (Van Rompaey et al., 2002).

Both soil erosion and sediment export to rivers and lakes are considered to be important environmental problems. Soil erosion is considered to deteriorate onsite soil quality in an irreversible way, which often results in a reduction of the production potential of the soil and may even be a driver of land-use change itself (Bakker et al., 2004, 2005b). Sediment export to rivers and lakes is considered to be a problem for various reasons. Often the sediment is polluted with fertilisers, leading to eutrophication and the disturbance of fragile water ecosystems. Increased sediment supply to rivers will lead to excessive sedimentation in lakes and reservoirs, thereby threatening aquatic life and/or hydroelectric power production (Douglas, 1995; Vanacker et al., 2003).

Given that the drivers for intensification or de-intensification and erosion and sediment export are often similar (e.g. slope, soil type, distance to rivers) the response of erosion and sediment export to land-use changes resulting from intensification or de-intensification is likely to be non-linear. For example, the conversion of an erosion-prone land-use to a non-erosion-prone land-use (e.g. the conversion of arable land to shrublands, which is a land-use conversion that is typical of de-intensification) occurring on steep slopes would amplify the positive effects of the land-use change for soil conservation. With respect to the connectivity between sediment source and river or lake, the spatial configuration of a land-use change within the landscape is also important. For accessibility reasons, arable cultivation is generally maintained longer near to villages, which are also often close to rivers, while the arable fields located further away from the villages (and therefore from the rivers) are the first to become abandoned. This would lead to a relatively small reduction in sediment export to the rivers, even though the overall onsite sediment production would decrease significantly.

A reliable estimate of the impact of land-use change on erosion and sediment export is thus only possible by accounting for the non-random nature of land-use change within a landscape. In this paper we study the response of soil erosion and sediment export to past land-use change in both intensive and less intensive agricultural areas. We quantify the importance of land-use change with respect to soil erosion and sediment export as well as the role of the land-use change patterns.

2. Materials and methods

Land-use change was analysed over the past five to six decades in four case study areas of Europe (Fig. 1). Three of the study areas were subject to de-intensification (in Portugal, France, and Greece) whilst the fourth (in Belgium) was intensively cultivated. The selected areas represent typical European areas, as identified by MacDonald et al. (2000). Erosion and sediment export to lakes and rivers were modelled using the WaTEM/SEDEM model.

2.1. Study areas

2.1.1. Amendoeira, Portugal

The Amendoeira area, named after the local village, is 4400 ha in size and is located in the Alentejo region (37°47 N, 07°40 E), southeast Portugal, near to the Spanish border. The topography, which does not exceed 200 m.a.s.l., is hilly, with generally short (50–100 m) slopes. The slopes in the vicinity of the Guadiana river, in the east of the area, are somewhat longer and steeper. The regolith soils formed on schist are very thin (0.05–0.10 m), have a low water holding capacity, and are strongly degraded and erosion-prone. The area has a typical Mediterranean climate with hot, dry summers; temperatures often attain 30°–40°, and humid winters, with precipitation up to 650 mm.

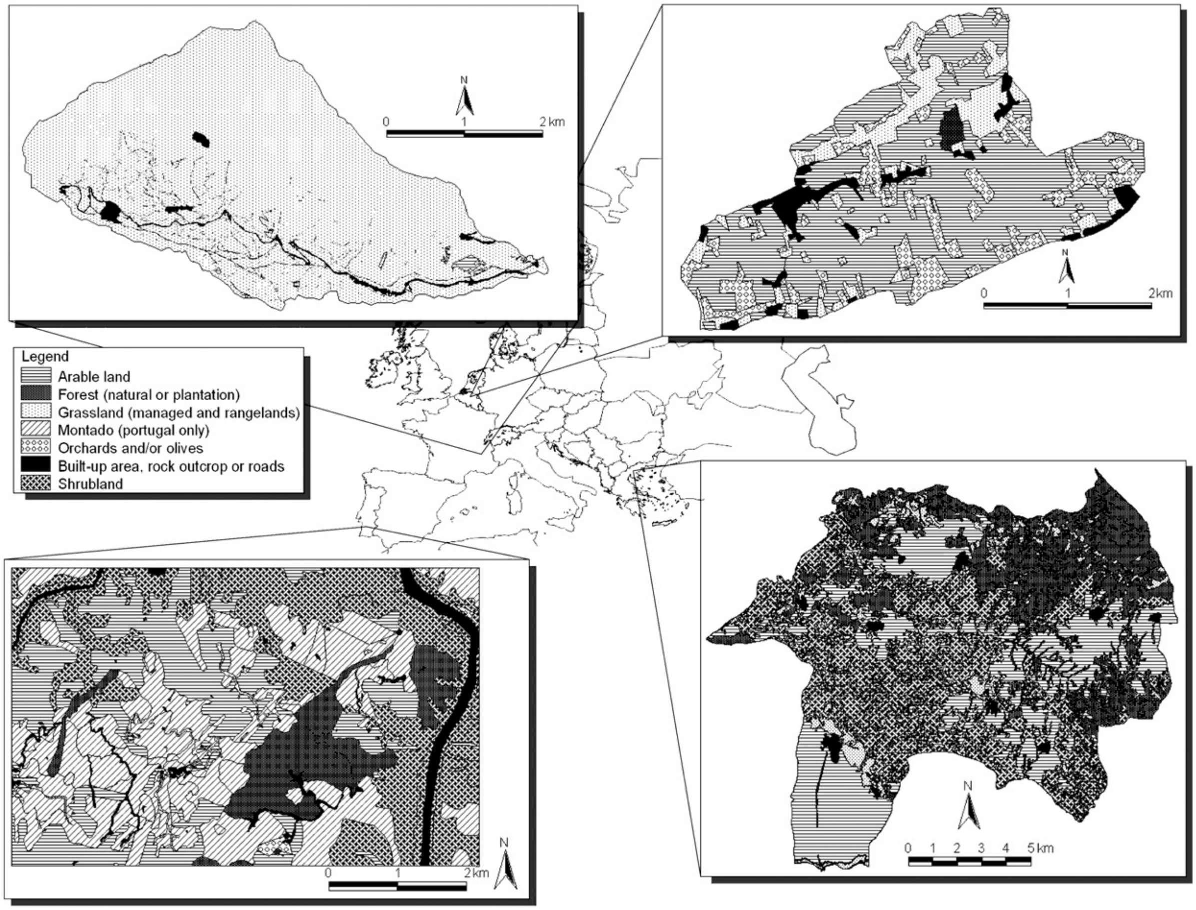

Fig. 1. The four case study areas (upper left: Lautaret, France; upper right: Hageland, Belgium; lower left: Amendoeira, Portugal; lower right: Lagadas, Greece).

The area has been subject to agricultural de-intensification. In the beginning of the 20th century the area was used for cereal production in combination with extensive livestock breeding. Even steep slopes were cultivated, which led to strong soil degradation. Since the 1950s the economic importance of cereal production and livestock breeding decreased, resulting in an increase in shrubs and natural pasture. The Common Agricultural Policy of the EU has significantly influenced today's land-use. Some fields have been (re-) used for cereals, although extensive livestock breeding (mainly sheep) is now more important. The conversion of former agricultural land into oak (*Quercus rotundifolia* and *Quercus suber*) and pine (*Pinus pinnea*) forest plantation is the most visible land-use change in the area. At present the landscape is characterised by patches of arable fields, natural pastures and different types of shrub lands, some parts being covered with open oak forest (*Q. rotundifolia*) of variable density, that creates the agro-silvo-pastoral system known as Montado (Pinto-Correia, 1993).

2.1.2. Lautaret, France

The Lautaret study site is set on the south-facing slope of a valley above the village of Villar d'Arêne (45.04°N, 6.34°E) in the French Alps. It covers 1292 ha in the headwater of the Romanche river. Stretching from approximately 1600 m to 3000 m.a.s.l., the site is characterised by strong altitudinal gradients. The upper slopes have shallow soils on homogeneous calcareous-shale bedrock. The lower slopes are essentially made of glacial till with some emerging ridges of calc-shale. Climate is sub-alpine with a strong continental influence due to a rain shadow effect arising from the dominant westerly winds. Mean annual rainfall is 956 mm and the mean monthly temperatures ranges from −7.4 °C in February to 19.5 °C in July.

Although the upper slopes (above 2500 m) have always been extensively grazed, the lower slopes have undergone land-use change in recent times. At the demographic maximum around 1830 (Rousset, 1977), arable fields covered the lower slopes (1650 to 2000 m) and large areas of natural grasslands were cut for hay at higher elevations (1800 to 2500 m). As mountain agriculture lost ground to more lucrative activities such as tourism, and the exodus of people from rural areas to the cities led to population decline (from the 1830s until the present), former arable fields were abandoned and subsequently converted to grasslands used for hay or grazing. The resulting landscape is dominated by natural grassland ecosystems (not cultivated) that are used for grazing by sheep. Some fields are still used for the production of potatoes for local consumption and for fodder crops (clover and Lucerne) (Parc National des Ecrins, 2004).

2.1.3. Lagadas, Greece

The Lagadas case study area is part of the Lagadas county, located around 30 km NE of the city of Thessalonica, Greece (23°19′, 40°44′). The area comprises five village communities and covers an area of about 24,551 ha. Altitude ranges from less than 100 m.a.s.l. in the south to more than 1000 m.a.s.l. in the northeast. The area has a sub-humid Mediterranean climate with cold winters with a mean annual precipitation around 500 mm and a mean minimum temperature in January below 0 °C. Gneiss is the dominant parent material and soil pH does not exceed 5.5. The topography is hilly, with a rather dense drainage pattern. Soil fertility and erodibility vary considerably within the area.

Land-use within the area has changed rapidly over the last 50–60 years. A strong increase in the area of arable land, shrubland and forest occurred at the expense of grasslands, which have decreased dramatically since 1945. A significant part of the grasslands that have converted into shrublands were used as grazing areas for goats and sheep and this, as well as fuel woodcuttings, has reduced. The establishment of farm forests through EU subsidies or the expansion of natural forest and shrubs over the borders of abandoned farms (mainly in less productive areas with steep slopes) promoted forest and shrubland expansion at the expense of grasslands. Furthermore the conversion of grasslands into arable land was stimulated by a policy in favour of agricultural production. Although shrubland areas increased at the expense of grassland and, to a lesser extent, at the expense of arable land, overall they have reduced in area as shrubland has also been converted to forest (Chouvardas et al., 2004).

2.1.4. Hageland, Belgium

The Hageland in Belgium differs from the other study areas as it has undergone agricultural intensification rather than de-intensification. The area is 1292 ha in size, and has a slightly rolling topography. The soils are generally very fertile and erodible due to their high silt-content. The topography does not lead to poor accessibility or workability. The area has a temperate climate with an average precipitation of 760 mm and a mean monthly temperature ranging from 0–5 °C in January to 18–22 °C in July. Precipitation is distributed throughout the year. The area was mainly under arable use early in the 20th century as a result of increasing population pressure, but problems of soil erosion and water-logging forced farmers to convert steep slopes and lower lying areas respectively to forest or grassland. After the introduction of inorganic fertilisers and European subsidies, arable production once more became profitable. Farmers brought steeper slopes back into cultivation and improved the drainage of the lower lying areas so that these too could be reconverted to arable land. The standard arable rotation system is cereals (wheat or barley) with maize or sugar beet, which is sometimes followed by a year of fallow land. Grasslands are mainly used for grazing by cows for meat production. More recently, orchards have been introduced, as they are more profitable than cereals and sugar beet.

2.2. Analyzing past land-use changes

Land-use maps of different time periods over the past five to six decades were compiled for each site (20 m resolution). In addition, data on landscape attributes were collected for two purposes: (i) to help identifying the spatial pattern of land-use change in relation to other attributes that determine erosion and sediment export within the landscape, and (ii) to run the erosion and sediment export model. For most sites these data comprise a digital terrain model, soil characteristics such as silt-content and soil organic matter, and distance to rivers (the Lautaret site lacks spatially explicit soil data, whereas the Lagadas site only has data concerning the hardness of the parent material).

The relationship between the land-use change and other landscape attributes determining erosion and sediment export was investigated using logistic regression analyses (SAS Institute Inc., 2001). The relationships were considered to be stationary. A sample of one point per hectare was drawn out from each map. A hectare is considered to be an independent spatial unit for which a farmer can make an autonomous decision, regardless of the surrounding land-use. By taking such a sample, overestimations of statistical significance levels are avoided that would otherwise have resulted from counting all pixels that represent one single land-use change event as individual observations.

Logistic regression was used to compare the erosion-determining landscape attributes at places where a land-use change has occurred (e.g. from arable to forest, shrub land or grassland) to those at places where no change has occurred (e.g. permanent arable land). The dependent variable was therefore presence (1) or absence (0) of a land-use change, with the independent variables being slope, soil silt-content, soil organic matter content and distance to rivers or water bodies. For the abandonment of arable land in the Lautaret area there were insufficient occurrences of "permanent arable land" for comparison with the observations of converted arable land. Thus, a cross-sectional analysis of the oldest map was conducted rather than a panel analysis (i.e. an analysis of the relationship between landscape and land-use rather than land-use *change*).

2.3. Erosion and sediment export modeling

For each period and each study area, erosion and sediment export to rivers and/or lakes were simulated using the WaTEM/SEDEM model (Van Oost et al., 2000; Van Rompaey et al., 2001). This model first calculates how much sediment is produced onsite by water erosion, by applying a 2-dimensional version of the RUSLE equation, and secondly how much of this sediment is transported to a river or lake on a yearly basis.

According to the RUSLE, mean annual erosion $= R\ K\ LS\ C\ P$ (Renard et al., 1997).

Where R = the rainfall erosivity factor ($\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}}$); K = the soil erodibility factor ($\mathrm{ton \cdot h \cdot MJ^{-1} \cdot mm^{-1}}$); LS = the topographic factor (−); C = the crop management factor (−); P = the erosion control practice factor (−).

For each site, a constant rainfall erosivity factor (R) was assumed which was derived from the rainfall data collected within the PESERA project (Jones et al., 2003) (Table 1). For the Hageland and the Amendoeira sites the soil erodibility factor (K) was calculated from soil maps that contained information about silt and organic matter contents. For the Lagadas site, the K-factor was derived from the hardness of the parent material (Institute of Geological and Mining Research (IGMR), 1979). For the Lautaret area the K-factor was calculated from the average silt percentage, and was considered to show no spatial variability (Table 1).

For the topographic factor (LS) a 2-D routing algorithm was applied in which the one-dimensional upslope length was replaced by a unit contributing area. At parcel borders the contributing area is lowered by 50%. The latter procedure is explained in detail by Desmet and Govers (1996) and Van Oost et al. (2000).

For each land-use type a crop management factor (C) was estimated from the literature and field observations. As arable land is a mixture (both in space and in time) of various crops, a long-term average value was computed by taking the average of the C-factor values of the most dominant arable crops grown in the four areas (Table 2). The C-factor for arable land in all areas was set to this average value of 0.3.

In the same way, dense grassland was set to a value of 0.01 and mature forest to 0.001. All other land-uses were ranked in between these values based on qualitative field observations (i.e. an estimate was made of the overall protection afforded by each vegetation cover). Based on these field observations, the C-factor of grasslands other than 'dense' grasslands varied from 0.05 for the high-altitude, unmanaged grasslands in Lautaret to 0.2 for the poor-cover grasslands in Lagadas. The young tree plantations in Amendoeira, where the soil is often less protected, were assigned a C-factor of 0.01 instead of 0.001. Other land covers such as olives, orchards and arable-Montado were assigned values between 0.1 and 0.25. Spatial and temporal variability of the erosion control practice factor (P) were not considered in this study, due to insufficient data about changes in management through time. In both Amendoeira and Lautaret, terraces exist(ed), but there is a lack of information concerning their extent and location through time. This assumption may result in an overestimation of soil erosion on arable land. An increase in erosion due to the abandonment of terraces was not considered in this study because the authors are not convinced that the abandonment of terraces leads to accelerated erosion as sometimes suggested in the

Table 1
RUSLE values per site

Site	LS (mean ± standard deviation)	R ($\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}}$)	K ($\mathrm{kg \cdot h \cdot MJ^{-1} \cdot mm^{-1}}$)	P
Amendoeira (Portugal)	5 ± 8	850	5, 17, 35, 52	1
Lautaret (France)	33 ± 38	800	37	1
Lagadas (Greece)	6 ± 7	650	20, 30, 40	1
Hageland (Belgium)	2 ± 50	550	12, 26, 29, 37, 41	1

LS = upslope contributing area according to the algorithm developed by McCool et al. (1987) and McCool et al. (1989).

Table 2
C-factor values per land-use

Land-use	Value	Source
Arable land		
Barley/oats	0.21	Literature[a]
Alfalfa (established)	0.02	Literature[a]
Peas/beans	0.32	Literature[a]
Potatoes	0.34	Literature[a]
Fallow	1.00	Literature[a]
Vegetable crops	0.43	Literature[a]
Grain corn	0.31	Literature[a]
Grapes	0.05	Literature[a]
Root crops	0.36	Literature[a]
Alfalfa/clover (cover crop)	0.08	Literature[a]
Grass/legume (cover crop)	0.16	Literature[a]
Tobacco	0.49	Literature[a]
Rye/wintherwheat	0.20	Literature[a]
Average	0.30	Literature[a]
Arable-Montado dense tree cover (Amendoeira)	0.20	Field observation
Arable-Montado medium tree cover (Amendoeira)	0.25	Field observation
Arable-Montado sparse tree cover (Amendoeira)	0.30	Field observation
Grasslands		
Managed grassland (Lautaret and Hageland)	0.01	Literature[b]
Unmanaged grassland (Lautaret)	0.05	Field observation
Grassland for extensive grazing (Lagadas)	0.20	Field observation
Grassland-Montado (Amendoeira)	0.01	Field observation
Forests		
Forest (Hageland, Lagadas, Amendoeira)	0.001	Literature[b]
Open forest (Lagadas)	0.01	Field observation
Oak plantation (Amendoeira)	0.01	Field observation
Orchards		
Orchard (Hageland)	0.05	Field observation
Olives (Amendoeira)	0.05	Field observation
Vineyards and orchards (Amendoeira)	0.20	Field observation
Shrublands		
Dense shrub (Amendoeira, Lagadas)	0.01	Field observation
Sparse shrub (Amendoeira, Lagadas)	0.10	Field observation
Not erodible		
Built-up area	0.00	a-priori assumption
Rock outcrops	0.00	a-priori assumption
Roads	0.00	a-priori assumption

[a] NS Department of Agriculture and Fisheries (2001).
[b] Renard et al. (1997).

literature (Lasanta et al., 2001). We believe that abandonment of terraces mainly involves mass movement rather than water erosion, and that the recuperation of protective vegetation cover takes place before any considerable erosion can occur on the abandoned terraces (Ruecker et al., 1998).

The values obtained for the *C*, *K* and *R* factors are coarse estimates. However, the principal aim of this study is to examine the temporal evolution of erosion and sediment yield. It is not necessary, therefore, that these values are highly accurate, but more that the relative erodibility of each land-use (configuration) is well represented. As the obtained *C*-factors and *K*-factors are good representations of the relative erodibility of each land-use, the nature of the response of erosion and sediment export to changes in land-use in time and space can be identified.

Sediment transport is calculated from the transport capacity of the path from the sediment source (e.g. arable field) to the sediment sink (river or lake). The model calculates for each pixel the mean annual sediment production and mean annual transport capacity. By means of a routing algorithm, each cell is connected with the river via a unique flow path. The produced sediment follows this flow path, and provided the calculated pixel transport capacity exceeds the incoming sediment volume, the sediment is transferred further downslope. When the calculated pixel transport capacity is lower than the incoming sediment volume, sedimentation occurs. Parcel boundaries act as sediment traps.

The pixel transport capacity is calculated for the slope, upslope contributing area, and the local land-use that determines the surface roughness. Surface roughness is given by a transport capacity coefficient (KTC). We assume a KTC value for arable land, and another one for non-arable land. Roads and rock outcrops are considered to have a very high transport capacity. No data were available for the sites studied that would allow the KTC values to be calibrated, but calibration results from previous studies show rather stable values around 75 m for grasslands and 250 m for arable land (Van Rompaey et al., 2003a,b). These values apply to the multiple flow version of WaTEM/SEDEM and to a pixel resolution of 20 m.

The outputs of the model are as follows: (i) onsite sediment production ($\text{ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), which is detached soil material that can be transported over a certain distance, (ii) sediment export ($\text{ton}\cdot\text{km}^{-1}\cdot\text{yr}^{-1}$), which is the amount of detached soil that reaches a river or lake and is therefore lost from the agricultural system, and (iii) the sediment delivery ratio, which equals the total sediment production ($\text{ton}\cdot\text{yr}^{-1}$) divided by net soil loss ($\text{ton}\cdot\text{yr}^{-1}$).

2.4. Analyzing the response of sediment production and export to land-use change

A *theoretical* relationship was constructed between sediment production and the average *C*-factor assuming that changes in *C*-factor values (i.e. land-use change) occur *independently* from other erosion-determining landscape attributes. This was done in order to identify the extent to which the response of sediment production and export to land-use change is controlled by spatial associations between land-use change and other erosion-determining factors. This approach was based on running the WaTEM/SEDEM model over the area for a single, randomly chosen, homogeneous value of the *C*-factor. In doing so, the *C*-factor was distributed independently from any other spatial variable. A straight line was fitted through the resulting values for the onsite sediment production and the origin, as (a) there will be no sediment production if the *C*-factor is zero and (b) the relationship between *C* and erosion is linear when *C* is not related to K, R, LS or P (see RUSLE equation).

Sediment production and sediment export were simulated for each period, using the *C*-factor maps derived from the historical land-use data. The results (average sediment production and sediment export for each area and each time period) were plotted against the *average* *C*-factor for each period. The curves obtained in this way were then compared to a theoretical, straight-line sediment production response. The response of sediment export to the average *C*-factor values is complex since the ratio between high transport capacity land-use (arable) and low transport capacity land-use (anything other than arable) is not captured entirely by the average *C*-factor. In this study only obvious deviations are analysed in the net soil loss/sediment export from the onsite sediment production curve. Such deviations should be attributable to changes in landscape pattern.

3. Results

3.1. Land-use change

Fig. 2 shows the change in total area under arable land, grassland, forest, shrubland and other land-uses for all four areas. It can be seen that for the Amendoeira and Lautaret sites, the total area under arable land has decreased in favour of forest, shrubland and (Montado) grassland. In Lagadas, grassland decreased in favour of shrubland and forests. Over a longer time span, Hageland shows no clear land-use changes, except for the introduction of orchards. Table 3 shows the dominant land-use changes (>5% of the area over the total period), together with the associated change in *C*-factor, and the erosion and sediment export-determining landscape attributes with which the land-use changes were found to be associated. The odds ratio is shown after each landscape attribute to indicate the nature and the magnitude of the association. Odds ratios represent the increase in observed frequency of a change (between 0 and 1) with one unit increase in the

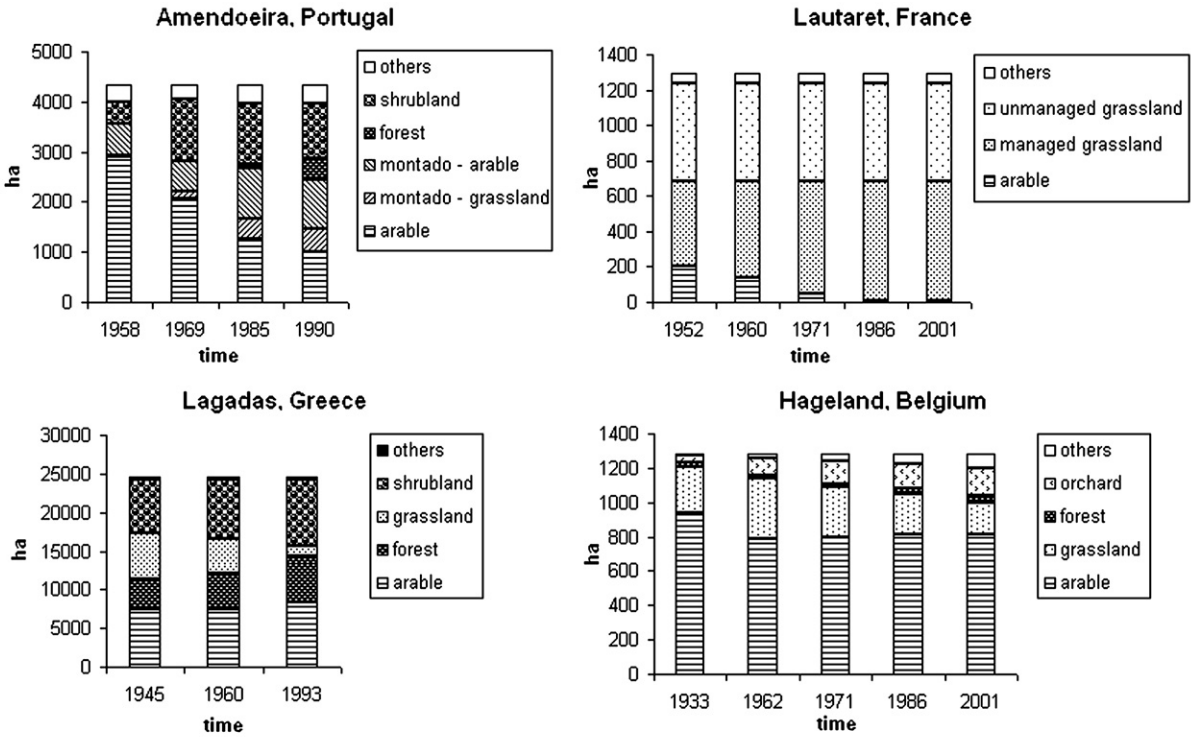

Fig. 2. Trends in land-use over the past decades for the four case study areas.

Table 3
Main observed land-use changes, associated C-factor changes and related erosion and sediment export-determining landscape attributes

Land-use change	Area (ha)	Associated C-factor change	Related erosion and sediment export-determining factors (odds ratio)			
			Slope	Silt-content	Organic matter	Distance to river
Amendoeira (Portugal)						
Arable to grassland-Montado	110	−0.2 to −0.29	1.186	0.856	0.829	0.999
Arable to arable-Montado	250	−0.05 to −0.2	–	0.974	0.972	–
Arable to holm oak	183	−0.29	1.128	0.817	0.810	0.999
Arable to cork oak	230	−0.29	–	0.935	0.951	0.999
Arable to shrubland	302	−0.2	1.327	0.672	0.654	0.999
Lautaret (France)						
Arable to grassland	196	−0.29	0.929	–	–	0.998
Lagadas (Greece)						
Arable to shrubland	84	−0.2 to −0.29	1.314	–		–
Shrubland to arable	118	0.2 to 0.29	0.849	0.197[a]		
Grassland to arable	416	0.1	0.896	3.016[a]		
Grassland to forest	124	−0.199		7.516[a]		0.996
Grassland to shrub	974	−0.1 to −0.19	–	3.732[a]		0.998
Hageland (Belgium)						
Arable to orchard	108	−0.25	–	1.032	NA	1.002
Grassland to arable	78	0.299	3.110	0.910	NA	1.002

[a] Combined effect of organic matter and silt-content, expressed as the soil erodibility (K-factor: $\text{ton·h·MJ}^{-1}\text{·mm}^{-1}$).

independent variable. Odds ratios smaller than 1 indicate a negative relationship between the variable and the occurrence of the land-use change, whereas odds ratios higher than 1 indicate a positive relationship. All reported associations are significant at the 0.05 confidence interval.

From the observed relationships it can be concluded that in the Amendoeira area arable land is converted to grassland-Montado on steeper slopes, on less fertile soils and in areas closer to the river. Arable land is converted to arable-Montado on poorer soils (lower silt-content and less organic matter), but not as poor as those selected for grassland-Montado. Holm oak replaces arable land at locations closer to the river, on steeper slopes and less fertile soils, whereas cork oak replaces arable land on slightly better soils (however still poorer than where arable is maintained) and does not have a preference for steeper slopes. Arable land is replaced by shrubland on the steepest slopes and the poorest soils, mainly at locations close to the river.

In Lautaret, the only land-use change was from arable land to managed grassland. Land that originally was arable was situated on relatively gentle slopes, at short distances from the river.

In Lagadas, the conversions of grassland to arable land and to shrubland are the dominant land-use changes. The first conversion occurs on relatively gentle slopes and on more fertile, but erodible soils. The second

Table 4
Average C-factor, onsite sediment production, sediment export and sediment delivery ratios

Year	Average C-factor value	Sediment production ($\text{ton·ha}^{-1}\text{·yr}^{-1}$)	Sediment export ($\text{ton·ha}^{-1}\text{·yr}^{-1}$)	Sediment delivery ratio
Amendoeira (Portugal)				
1958	0.25	48.81	4.67	0.10
1969	0.20	32.07	2.61	0.08
1985	0.17	22.86	2.45	0.11
1990	0.15	20.52	2.89	0.14
Lautaret (France)				
1952	0.07	60.66	3.29	0.05
1960	0.06	44.01	2.76	0.06
1971	0.04	33.11	1.18	0.04
1986	0.03	28.88	0.92	0.03
2001	0.03	28.34	0.87	0.03
Lagadas (Greece)				
1945	0.15	14.28	8.58	0.60
1960	0.15	13.52	7.98	0.59
1993	0.13	12.65	6.93	0.55
Hageland (Belgium)				
1933	0.20	15.34	6.51	0.42
1962	0.19	11.40	4.55	0.40
1986	0.20	11.01	3.90	0.35
2001	0.24	11.14	7.29	0.65

conversion also occurs on the more erodible soils and closer to rivers. Grassland is sometimes also replaced by forest, and this occurs on more erodible soils, closer to the streams. Abandonment of arable land at the expense of shrubland occurs on steep slopes, whereas the reallocation of shrubland to arable occurs on more gentle slopes and on less erodible soils.

In Hageland, the main conversions are from arable to orchard and from grassland to arable. Both conversions occurred away from the streams. Arable land declines on silty soils, as the conversion of arable land to orchard occurs in these areas whereas the conversion of grassland to arable land occurs on less silty soils. In addition, most of the grassland converted to arable is situated on steep slopes.

3.2. Erosion and sediment export processes in the four areas

Table 4 shows the average *C*-factor value, the onsite sediment production, the sediment export and the sediment delivery ratio for each site. The estimated onsite sediment production rates in Amendoeira vary from 48.81 ton·ha^{-1}·yr^{-1} in 1958 to 20.52 ton·ha^{-1}·yr^{-1} in 1990. Sediment export to rivers varies from 4.67 ton·ha^{-1}·yr^{-1} in 1958 to 2.89 ton·ha^{-1}·yr^{-1} in 1990. Erosion and deposition generally occur close to one another because of the hilly landscape. This causes a rather low sediment delivery ratio, as much of the eroded sediment is deposited close to its source.

In Lautaret the estimated average sediment production rates vary from 24 ton·ha^{-1}·yr^{-1} at higher altitudes to deposition rates around 9 ton·ha^{-1}·yr^{-1} in the flatter area near the river (Table 3). The high erosion rates at higher altitudes can be ascribed to the long steep slopes without parcel boundaries. The land-use here is unmanaged grasslands, for which observations indicated are much less densely covered than the managed grasslands. In these areas strong gully formation occurs. Most of this sediment is deposited downslope, where a slope-break decelerates the sediment flow and where parcel boundaries reduce slope-length and trap sediment. Even in the arable fields, deposition is the dominant process. Because of the combination of morphology and land-use, the sediment delivery ratio is rather low, varying from 0.05 in 1952 to 0.03 in 2001, so that net soil losses are low, varying from 3.3 ton·ha^{-1}·yr^{-1} in 1952 to less than 1 ton·ha^{-1}·yr^{-1} in 2001.

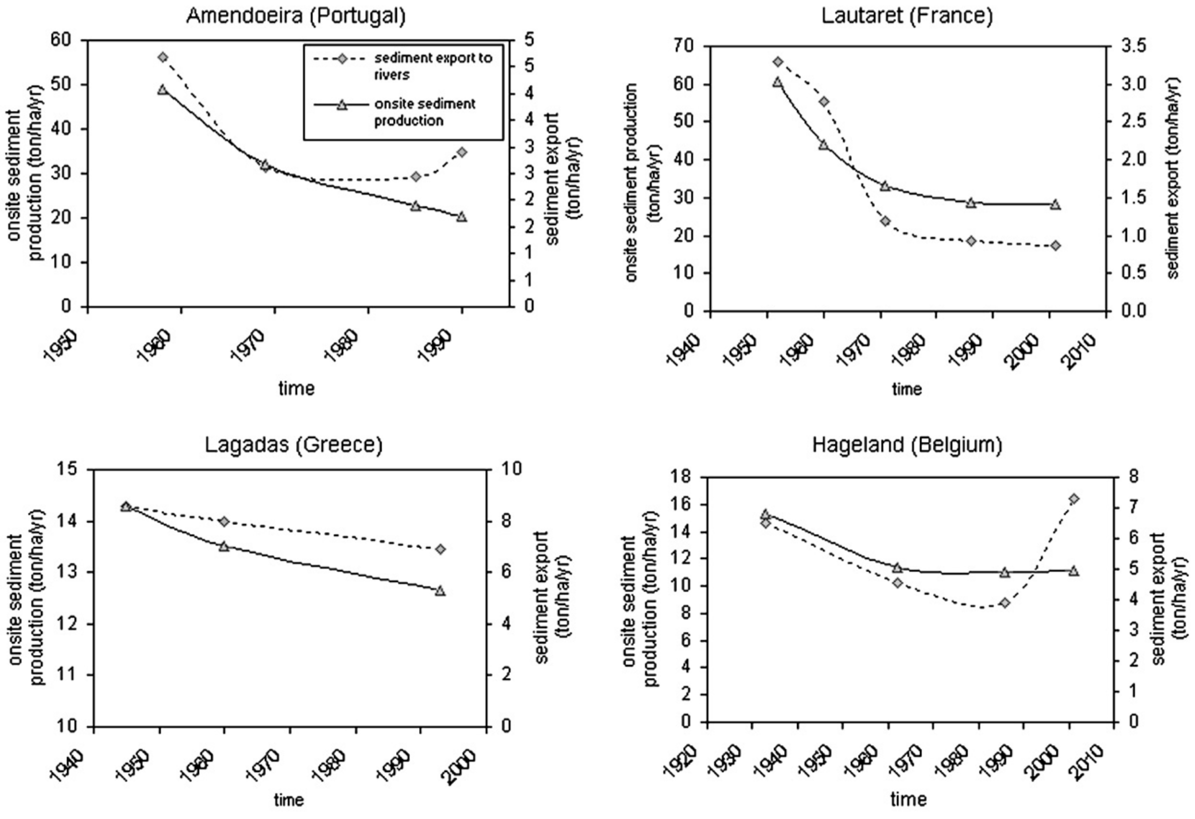

Fig. 3. Temporal evolution of onsite sediment production and export to rivers for the four case study areas.

The estimated onsite sediment production rates in Lagadas are relatively low due to low erodibility of the soils and vary from 14.3 ton·ha^{-1}·yr^{-1} in 1945 to 12.6 ton·ha^{-1}·yr^{-1} in 1990 (Table 3). However, as the sediment delivery ratio is high due to the dense drainage pattern, sediment export is high, varying from 8.6 ton·ha^{-1}·yr^{-1} in 1945 to 6.9 ton·ha^{-1}·yr^{-1} in 1990.

Hageland is the area with the lowest relief per unit area, and average onsite sediment production rates are therefore relatively low, varying from 15.34 ton·ha^{-1}·yr^{-1} in 1930 to 11.01 ton·ha^{-1}·yr^{-1} in 1986 (Table 3). The sediment delivery ratio is however quite high, leading to a relatively high net soil loss (6.51 ton·ha^{-1}·yr^{-1} in 1930 to 7.29 ton·ha^{-1}·yr^{-1} in 2001). The high sediment delivery ratio is caused by the unfavourable location of arable land with respect to sediment transport zones.

3.3. The response of sediment production and export to land-use change

Fig. 3 shows for each site the sediment production and sediment export as a function of time. It should be noted that the changes are solely due to changes in land-use, as no changes in climate or management has been taken into account. It can be seen that both erosion and sediment export decrease considerably with time, except for the intensively cultivated area of Hageland.

In Fig. 4 the onsite sediment production and the net soil loss are plotted as a function of the average *C*-factor value for each site. The grey line shows the theoretical response of onsite sediment production to *C*-factor changes (i.e. land-use change), if these occur independently of the other RUSLE factors. In reality, however, strong deviations from the reference line can be observed for both onsite sediment production and net soil loss in Amendoeira and in Hageland. Lagadas shows no clear deviations, whereas in Lautaret the first reductions in *C*-factor have lead to a stronger response of erosion and sediment export than later reductions in *C*-factor.

4. Discussion

4.1. Evolution of erosion and sediment export in de-intensified and intensified areas

De-intensification of marginal agricultural areas in Europe has resulted in a strong decrease in arable land in

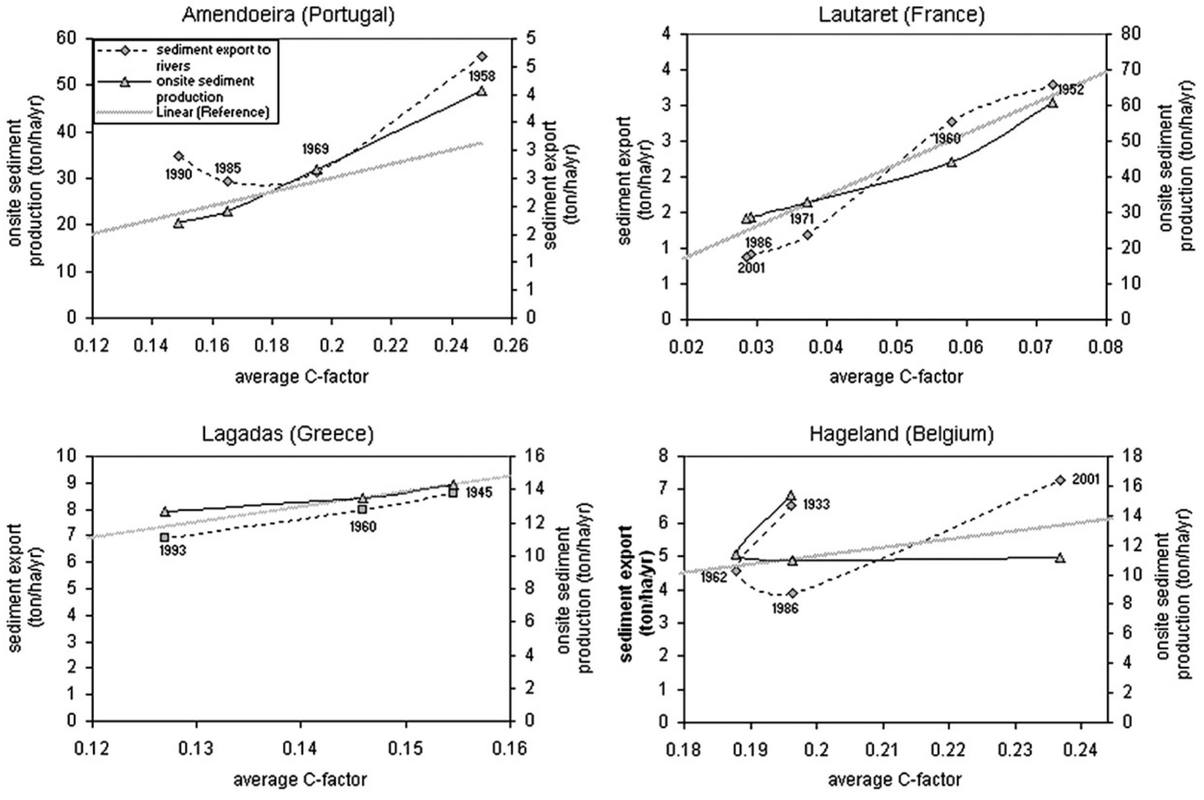

Fig. 4. Non-linearity in response of onsite sediment production and export to rivers to land-use change for the four case study areas.

favour of less intensive land-uses (e.g. shrubland, forests and grasslands). These land-use conversions have led to a large decrease in soil erosion and sediment export to rivers in such areas. De-intensification generally leads to an increase in protective vegetation cover so that onsite sediment production decreases, whereas sediment transport capacity reduces resulting in further reductions in sediment export in absolute terms, but also relative to the onsite sediment production. The Hageland area, which is intensively cultivated, did not show a comparable increase in erosion and sediment yield: even here in this intensive agricultural area a (relatively small) decrease in sediment production was noted. Intensification of land-use, which is often blamed for increasing water erosion rates (for example by increases in field size), is largely compensated for by the conversion of relatively small areas from arable land to pasture or forest. Thus, the large decrease of erosion and sediment export rates in marginal areas is not reflected in an equally large increase in intensively cultivated areas.

4.2. The role of the spatial configuration of land-use change

Fig. 4 demonstrates that the location of land-use change within the landscape has as much, if not more, impact on erosion and sediment export than the total area of land-use change. In order to gain insight into the different processes responsible for the deviation from the grey reference line, we have undertaken a study of the deviations of the erosion and sediment response to *C*-factor for (i) the Amendoeira case study as an de-intensified agricultural area and (ii) the Hageland case study as an intensively cultivated area.

4.2.1. Amendoeira

Land-use changes in the period 1958–1969 were characterised by large conversions from arable land to shrubland. As a consequence, both erosion and sediment export reduced significantly. The reduction was stronger than would have been the case if the reduction in *C*-factor had occurred randomly over the other RUSLE factors. Table 3 shows that this can be explained by the fact that the arable-shrub conversion mainly takes place on steep slopes. Although these soils have lower silt-content and should therefore be less erodible, they also have less organic material, which may compensate for the effect of less silt.

In 1958 the simulated onsite sediment production was higher than would have been the case if the *C*-factor were distributed randomly over the landscape. This is because arable land was situated on soils with a higher silt-content than average (18% silt in arable land vs 13% silt on average). In 1969 the onsite sediment production more or less equal as would have been the case if the *C*-factor were distributed randomly over the landscape. It appears that the abandonment of arable land on steep slopes counterbalances the fact that the abandonment also occurred on less erodible (low silt-content) soils. This can be explained partly because these soils also have lower organic matter content, and partly because the effect of slope is bigger than that of soil erodibility.

Onsite sediment production reduced as a result of a reduction in *C*-factor, and sediment export reduced further because the average transport capacity also reduced as a result of the reduction in arable land. Furthermore, as the areas closer to the river were more often converted to shrubland the connectivity between sediment source and sink was reduced, which explains the decrease in sediment delivery ratio.

During the period 1969–1985 arable land was replaced by both grassland-Montado and arable-Montado, which in both cases reduced the *C*-factor. Erosion decreased further as a response to the reduced *C*-factor. The conversion from arable to grassland-Montado involved the largest reduction in *C*-factor. In Table 3 it can be seen that this conversion occurred on steeper slopes and is therefore more beneficial for soil conservation. The fact that the converted soils are less erodible again appears to be of less importance. The conversion from arable to arable-Montado is not related to topography and occurs almost exclusively on non-erodible, poor sandy soils. It has therefore much less effect on erosion.

Although the total sediment production decreased in this period, the sediment export did not decrease, even though the conversion from arable to grassland-Montado occurred close to the river. The *C*-factor increased at certain locations very close to the river, due to a local conversion of shrubland or grassland-Montado to arable or arable-Montado. It appears that a seemingly unimportant land-use change, in terms of total area change, can lead to important (relative) increases in sediment export to rivers if it occurs at a particular location.

The period 1985–1990 is characterised by the introduction of cork and holm oak plantations. These conversions occur close to rivers, on less steep slopes and on soils with high organic *C*, but low silt-content. During this period, onsite sediment production and sediment export to rivers increased despite a reduction in the average *C*-factor value.

The forestation took place on areas that are not very susceptible to erosion. The small reduction in erosion risk due to forestation was more than compensated for by small reallocations of arable land from areas that were not erosion-prone to areas that are erosion-prone.

4.2.2. Hageland

In the intensively cultivated case study area in the Hageland, land-use changes have not resulted in an obvious decrease in erosion or sediment export. Although land-use changes have occurred, these mainly concerned exchanging between land-uses within the area. The total areas covered by a particular land-use remained, therefore, rather stable (Fig. 2).

Remarkably, the conversion of grassland to arable occurs mainly in areas that are traditionally unfavourable for arable cultivation (i.e. on steep slopes and non-fertile soils, Table 3). This phenomenon may be typical of intensively cultivated areas: areas that were once converted to less intensive land-use due to physical limitations are converted back to more intensive land-use once new technologies allow them to be cultivated again. In this case areas with low silt-content on steep slopes were converted back to arable land as fertilisers and stronger tractors allowed arable cultivation in these areas.

The response curve of onsite sediment production and export to changes in *C*-factor is irregular (Fig. 4). Of note is the decrease in sediment production and net soil loss in the period 1962–1986, while the average *C*-factor increased. It was found that arable land was converted to orchards on very steep slopes, which represented a large sediment source in 1962. Despite the fact that the average *C*-factor increased, certain reductions in *C*-factor at crucial places (former sediment sources) reduced sediment production and export. This behaviour could not be anticipated based on Table 3, from which was assumed that increases in *C*-factor (grassland to arable) occurring on steep slopes would have a relatively large effect on sediment production. The fact that increases in *C*-factor occur further away from the stream (i.e. with a relatively small effect on net soil loss) is in agreement with decrease in sediment export observed during this period.

In the period 1986–2001 there was a strong increase in average *C*-factor, accompanied by a strong response in sediment export, while onsite sediment production remained largely unchanged. The increases in *C*-factor (e.g. grassland to arable) mainly occurred on flat areas and this explains why onsite sediment production hardly responds at all. These relatively flat areas are close to the river: their conversion to arable land implies a reduction in buffering capacity, so that more sediment that is produced upslope can reach the river.

5. Conclusions

A simulation of erosion response to land-use change in four typical European areas during the last 50 years, showed that de-intensification of land-use in marginal agricultural areas has strongly reduced erosion and sediment export to rivers. This reduction is often amplified by the conversion of an erosion-prone land-use to a less erosion-prone land-use (e.g. the conversion of arable land to forest) on steeper slopes. Arable land is often maintained the longest on suitable, but erodible (silty) soils and the abandonment of arable land occurs earlier on less suitable, but also less erodible (sandy and clayey) soils. However, the topographical effect dominates the overall regional erosion response.

In general, de-intensification leads to a more favourable configuration of land-use within the landscape with respect to erosion and sediment export, as drivers of abandonment of arable cultivation and erosion coincide. However, the internal dynamics of land-use within the studied areas may lead to unexpected outcomes. The Portuguese case study illustrates that a simple conversion of arable land to forest may sometimes even result in an increase in erosion and sediment export, simply because of where these changes occur.

In the intensively cultivated Hageland area, there has hardly been an increase in erosion. This is because a) intensification in this case refers more to increases in inputs and in productivity rather than increases in the surface area of arable land, and b) the area is inherently much less erosion-prone than the other areas, mainly due to more favourable topography.

Hence, when comparing the de-intensified areas with the intensified area, it appeared that the erosion increase in intensified areas is not offset by far by the erosion-decrease in de-intensified areas. This implies that what is observed within the areas (i.e. optimisation of the land-use within a landscape) may also happen at a broader, European scale. As distribution mechanisms of agricultural products have improved strongly over the last 50 years (Chisholm, 1995), the area over which an optimal land-use configuration can be sought has become wider. This optimisation of land-use at the European scale involves large-scale abandonment of mountainous areas (MacDonald et al., 2000), while production shifts to areas that are more suitable for intensive cultivation and less erosion-prone at the same time. This extrapolation from the landscape scale to the broad, continental scale should nevertheless be made with caution, as global land-use optimisation often involves other processes that are not beneficial to erosion and sediment export to rivers (e.g. increasing parcel size, more intensive tillage and more aggressive herbicides and pesticides).

Based on the outcomes of the present study it may be argued that soil erosion in Europe is decreasing. The reduction in sediment production and export to rivers due to the de-intensification of some agricultural areas has not been offset by increases in sediment production and export due to intensification elsewhere. This is because intensification has probably occurred in areas that are much less erosion-prone with respect to the physical landscape characteristics. Thus, the research presented here emphasises that when undertaking broad-scale assessments of soil erosion, the broad-scale dynamics of land-use change should be taken into account, otherwise attention will only be given to those areas where problems are increasing, thereby neglecting reduction in erosion in other regions.

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