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• *Land-cover patterns – Erosive slope length – Soil erosion modelling – RUSLE*

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Effects of Land-Cover Change on Soil Erosion in the Saxon Switzerland National Park Region

Auswirkungen von Landnutzungsänderungen auf die Bodenerosion in der Nationalparkregion Sächsische Schweiz

With 2 Photos, 6 Figures and 4 Tables

Land-cover patterns changed significantly during the last century due to anthropogenic impact. This also affected soil erosion rates. Changes in land-cover patterns influence slope lengths and, thus, erosional displacement. However, this effect is not yet well quantified. There are various established approaches for the empirical modelling of soil erosion, but none seems appropriate to sufficiently consider changes in land-cover patterns. Our main objective is to quantify the effects of land-cover changes on soil erosion. Based on historical maps and physical factors, mainly soil properties and precipitation, our modelling techniques utilise Geographic Information Systems (GIS) to assess these effects, using the Saxon Switzerland ("*Sächsische Schweiz*") National Park Region during the past century as a test area. Our results indicate that changes in land-cover patterns affected soil erosion to a greater extent than estimated so far, and thus need to be considered more precisely in erosion modelling.

1. Introduction

Land use and land cover changed considerably during the last centuries (*Diemann* and *Arndt* 2001; *Ramankutty* et al. 2006; *Turner* et al. 2007), with industrialisation and extension of agricultural land being the major driving factors (IPCC 2000; *Foley* et al. 2005). Such changes affect environmental processes such as surface runoff (*Foley* et al. 2005) or regional weather patterns (*Pielke* et al. 2007; *Schneider* and *Eugster* 2007). These, on their parts, impact soil erosion, an anthropogenic process that is caused primarily by land use (*Bork* et al. 1998). Assessing the impacts of these changes helps quantify soil erosion and mitigate hazardous land-use and land-cover changes in the future (*Lambin* and *Geist* 2006).

Following IPCC (2000) and *Lambin* and *Geist* (2006), we define land cover (e.g., farmland) as the biophysical attributes of surface (e.g., albedo), and land use as the human use and managing of the land cover (e.g., tillage, grazing) (*Lambin* and *Geist* 2006). Changes in land use are often, but not necessarily always, associated with changes in land cover (IPCC 2000).

Soil erosion is largely triggered by surface runoff generated by intense convective precipitation events (*Schwertmann* et al. 1987; *Renard* et al. 1997; *Richter* 1998). The impacts of land use and land cover on soil erosion have been widely investigated, subjected to modelling techniques (*Renard* et al. 1997; *Schäuble* 1999; *Wilson* and *Lorang* 1999; *Schmidt* 2001; *Foster* et al. 2003; *Evans* and *Brazier* 2005; *Nearing* et al. 2005; *Szilassi* et al. 2006; *Bonilla* et al. 2007; *Flanagan et al.* 2007). Modelling soil erosion is an alternative to measurements of sediment yields (*Deumlich* et al. 2006), to quantify the displacement of soil through erosive processes, which may be either wind or water. Here we focus on water-induced soil erosion as the dominating erosional process in Central Europe (*Bork* et al. 1998; *Schmidt* 2001; *Boardman* 2006) and Germany (*Deumlich* et al. 2006).

There are two different types of soil erosion models, physical and empirical. Physical, process-based models such as EROSION 2D/3D, the Water Erosion Prediction Model (WEPP) or the Precision Agricultural-Landscape Modelling System

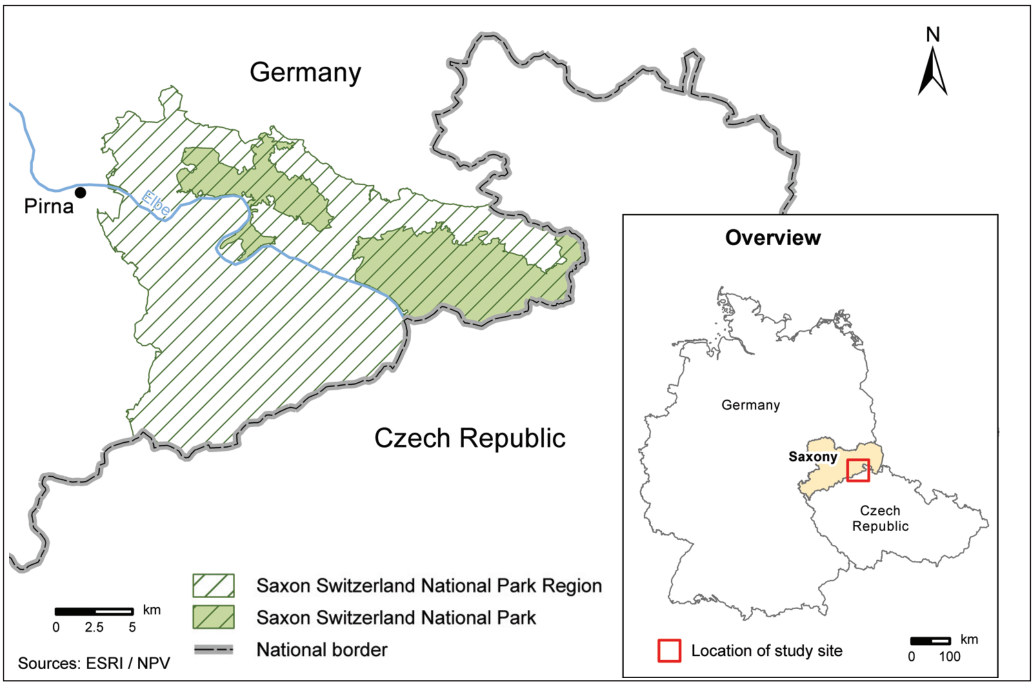

Fig. 1 Location of the Saxon Switzerland National Park Region
Lage der Nationalparkregion Sächsische Schweiz

(PALMS). They provide accurate erosion estimates based on hydrological and physical parameters (*Michael* 2000; *Schmidt* 2001; *Michael* et al. 2005; *Bonilla* et al. 2007; *Flanagan et al.* 2007). Due to their complexity, these models require many input parameters with high spatial and temporal resolution and are, thus, mainly used for single events on a plot scale (*Michael* 2000; *Schmidt* 2001; *Bonilla* et al. 2007).

Empirical models, such as the widely used Revised Universal Soil Loss Equation (RUSLE), assess long-time average soil losses (*Renard* et al. 1997) and may be used for larger areas up to the regional scale. Utilising statistically derived functions from standardised experimental plots, they depend on fewer input parameters, e.g., relief, rainfall, soil structure, management (*Schmidt* 1998), but are less accurate compared to the complex models described above (*Schmidt* 1998; *Michael* 2000). However, because they are easily applied and require widely accessible parameters, they are more frequently used to assess soil erosion (*Renard* et al. 1997; *Bork* et al. 1998; *Schäuble* 1999; *Schmidt* 2001), particularly for larger areas and annual time scales (*Bonilla* et al. 2007).

Changes in land use and land cover over time are commonly derived from remote sensing (*Cebecauer* and *Hofierka* 2008) or historic maps (*Schäuble* 1999; *Schmidt* 2001; *Jordan* et al. 2005; *Szilassi* et al. 2006), assuming other factors being invariant (*Schäuble* 1999; *Schmidt* 2001; *Jordan* et al. 2005; *Cebecauer* and *Hofierka* 2008). However, the effect of land-cover patterns, which have an impact on the energetic potential of surface runoff and consequently on soil erosion, is not considered in most studies. Common soil erosion models consider the importance of land-cover patterns as small (*Schäuble* 1999; *Hickey* 2000; *Schmidt* 2001). Nonetheless, transport potential of surface runoff increases with slope length, which is primarily regulated by the patterns of land cover. The longer the slopes within a given homogeneous land cover type, the greater is the erosive slope length. Consequently, changes in land-cover patterns may affect soil erosion considerably.

We therefore hypothesise that soil erosion is notably influenced by changing land-cover patterns. Furthermore, we hypothesise that soil erosion potential is underestimated in common empirical models as land-cover patterns are not adequately considered. Thus, we developed a method to include land-cover patterns in soil erosion modelling and tested it with a case study in the Saxon Switzerland National Park Region (*Fig. 1*) for the last century. Although this study area is not dominated by arable land, the Saxon Switzerland National Park Region has experienced enormous, well-documented changes in land use and land cover over the last centuries.

2. Material and Methods

2.1 Study area

The Saxon Switzerland National Park Region (about 51°N, 14°E) is a landscape protection area in the southern part of eastern Germany (*Fig. 1*). Most of the 380 km² area belongs to the Elbe Sandstone Mountains ("*Elbsandsteingebirge*") on both sides of the Elbe river. Mean annual precipitation ranges from 700 to 800 mm with a summer maximum (*Kaulfuß* and *Kramer* 2000; *Flemming* 2001). A structured terrain (*Fig. 2*), derived from sandstone, fostered poor, usually forested soils (*Tröger* 2006). Arable soils are mainly related to periglacial loess on plateaus (21 % of the area, *Photo 1*). In the past, agriculture and forestry dominated the area, with the former, in particular, having changed significantly over the last century (*Fichtner* 2005).

2.2 Land-cover change

We assessed changes in land cover and land-cover patterns based on digitised historical maps from 1900, 1940 and 1992. Historical maps were available

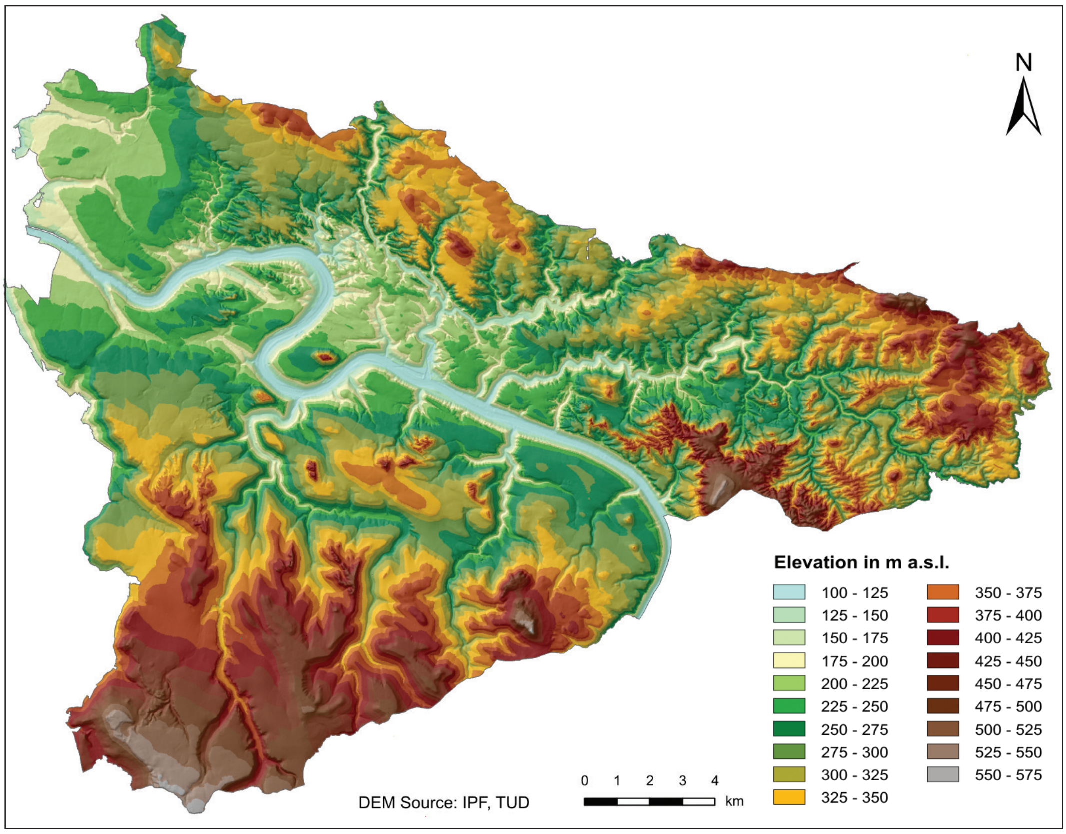

Fig. 2 Relief map of the Saxon Switzerland National Park Region
Höhenschichtenkarte der Nationalparkregion Sächsische Schweiz

back to 1780 (see *Witschas* 2002 and *Fichtner* 2005 for details), however, the use of these maps failed because of inaccuracies including different aggregation scale and discrepancies in georeferencing. These inaccuracies considerably affected slope length calculations and caused difficulties in the comparison to the maps from 1900 to 1992, so pre-1900 data was not used in the final analysis.

The Geographic Information Systems (GIS) ArcGIS 9.1 (ESRI) and the open source GIS SAGA 2.0 were used to assess land-cover changes (calculation of area and number of agricultural units) and for modelling soil erosion.

2.3 Soil erosion modelling with RUSLE

The empirical Revised Universal Soil Loss Equation (RUSLE) (*Wischmeier* and *Smith* 1978; *Renard* et al. 1997) estimates the longtime average annual soil loss in t/ha/a (A) by the equation

$$A = R \times K \times S \times L \times C \times P \qquad (1)$$

where R denotes the Rainfall-runoff erosivity factor (R-Factor), K the Soil erodibility factor (K-Factor), S the Slope steepness factor (S-Factor), L the Slope length factor (L-Factor), C the Cover-management factor (C-Factor) and P the Support prac-

Photo 1 Agricultural use of loess plateau near Reinhardtsdorf
Landwirtschaftliche Nutzung einer Lössebene bei Reinhardtsdorf

tise factor (P-Factor). *Schwertmann* et al. (1987) adapted RUSLE to Central Europe. Besides RUSLE, there are simplified versions that regard certain factors as constant (*Marks* et al. 1992; *Hennings* 2000) or even exclude factors (see DIN 19708; *Hennings* 2000). We also used such simplification for our case study (C-Factor and P-Factor = 1) and assumed slope length as the only variable factor in time (1900-1992).

Precipitation data from 1961 to 1990 collected at 18 stations were corrected (for wind according to *Richter* 1995) and regionalised with a regression analysis related to topography based on a Digital Elevation Model (DEM) with a spatial resolution of 20 meter. Because of the higher relevance for soil erosion, only summer precipitation was used (see *Schwertmann* et al. 1987) for the regionalisation. Mean annual precipitation (*P*, in mm) was regionalised by the equation

$$P = 378.4 + \frac{24.2}{100} \times h \qquad (2)$$

where *h* is elevation ($R^2 = 0.5587$); furthermore, orographic Luv-Lee adaption was applied. Based on this dataset and regional adaptations for Saxony, the R-Factor (*R*) was calculated according to DIN 19708 (2005) using

$$R = 0.2755 \times N_S - 50.03 \qquad (3)$$

with N_S being mean annual summer precipitation in mm ($R^2 = 0.972$).

K-Factors were derived from digital soil maps (*Hennings* 2000; DIN 19708 (2005). We calculated S-factors (*S*) based on slope angles (β) derived from a 5-m DEM (selected here to account for the needed greater spatial resolution, *Schwertmann* et al. 1987; *Hickey* 2000; *Claessens* et al. 2005), using the equation of *Nearing* (1997)

$$S = -1.5 + \frac{17}{1 + e^{2.3 - 6.1 \sin \beta}} \qquad (4)$$

Unfortunately, the 5 meter DEM only covered about 90 % of the study area (see also *Fig. 5*).

2.4 Modelling erosive slope length

Estimating erosive slope length is often referred to as the most complicated part of erosion model-

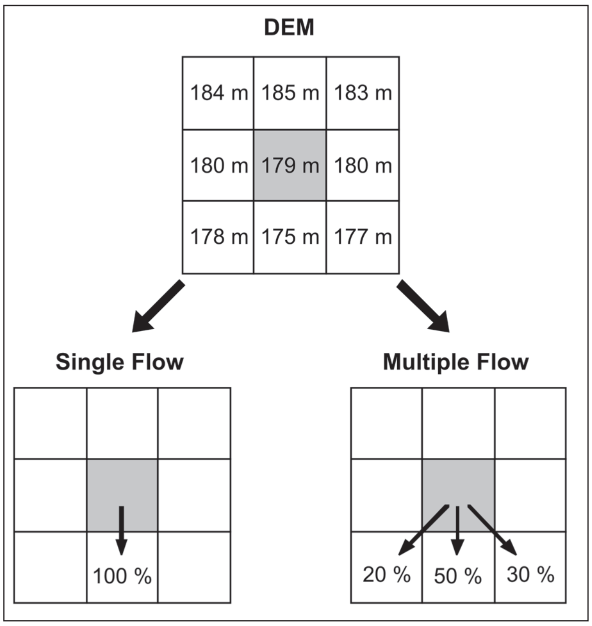

Fig. 3 Types of flow direction algorithms: Single Flow versus Multiple Flow (DEM = Digital Elevation Model, numbers indicate elevation in m a.s.l.; grey box is the origin of runoff, arrows indicate its forwarding according to the type of flow algorithm.) / *Typen von Fließrichtungsalgorithmen: Single Flow versus Multiple Flow (DEM =Digitales Geländemodell, die Zahlen geben die Höhe in m über NN an; die graue Box kennzeichnet den Ursprung des Abflusses, die Pfeile zeigen die Weiterleitung entsprechend dem Typ von Fließrichtungsalgorithmen an.)*

ling (*Moore* and *Wilson* 1992; *Renard* et al. 1997; *Wilson* and *Lorang* 1999; *Hickey* 2000). Determination in the field is only feasible for selected slopes (*Hickey* 2000). Hence, average slope lengths are usually assumed (*Schäuble* 1999; *Hennings* 2000; *Hickey* 2000), neglecting any heterogeneity. Accordingly, effects of land-cover patterns cannot be considered. Previous approaches for slope length calculation (*Moore* and *Wilson* 1992; *Desmet* and *Govers* 1996; *Schäuble* 1999; *Wilson* and *Lorang* 1999; *Hickey* 2000) usually caused difficulties, in particular related to software (*Schäuble* 1999). In general, slope length is evaluated from a DEM via flow directions of surface runoff (*Schäuble* 1999; *Hickey* 2000; *Van Remortel* et al. 2001). Other approaches are based on the Unit Stream Power Equation by *Moore* and *Burch* (1986) (see *Moore* and *Wilson* 1992; *Mitasova* 1993; *Mitasova* et al. 1996; *Mitasova* et al. 2001; *Schmidt* 2001) or use upslope catchment area as a substitute for slope length (*Desmet* and *Govers* 1996; *Wilson* and *Lorang* 1999; *Hickey* 2000). In all approaches, surface runoff modelling is the key to determining proper slope lengths for soil erosion modelling.

2.5 Modelling surface runoff

The major two algorithms for modelling surface runoff based on a DEM (*Wilson* and *Lorang* 1999) are (1) Single Flow Direction (SFDA) and (2) Multiple Flow Direction (MFDA) algorithms (*Fig. 3*). Deterministic 8 (D8) by *O'Callaghan* and *Mark* (1984) is the established SFDA (*Schäuble* 1999; *Wilson* and *Lorang* 1999). With FD8, *Freeman* (1991) proposed the most common MFDA so far. Whereas SFDAs can only forward runoff in one particular direction, MFDAs facilitate multiple directions and are thus more realistic, although they are less easily implemented. The latter allow computing runoff divergences rather than just convergences, and produce fewer artificial water divides. One disadvantage regarding divergence in some MFDAs is the diffusion of surface runoff on flat terrain (like valley floors). This problem can be solved by using a SFDA only in those particular areas and is referred to as combined flow (*Quinn* et al. 1995; *Schäuble* 2003). The lack of implementation of MFDAs in standard GIS software calls for additional tools or GIS extensions, e.g., HydroTools for ArcView 3.3, TauDEM for ArcGIS or Open Source GIS like SAGA.

Based on the types of algorithms to model surface runoff, two calculation approaches for slope length can be distinguished: flow length based (FLA) and catchment based (CMA) approaches. Examples of FLAs are the Irregular Slope Concept by *Schäuble* (1999) and the methods of *Hickey* (2000) and *Van Remortel* et al. (2001). *Moore* and *Wilson* (1992), *Desmet* and *Govers* (1996) and the Unit Contribution Area Concept by *Schäuble* (1999) are examples of CMAs. While FLAs are based on SFDAs, CMAs almost entirely rely on MFDAs. However, in general CMAs could also be used with SFDAs, but would then incorporate the associated disadvantages of SFDAs. A more detailed discussion of algorithms, tools for modelling surface runoff with GIS, and calculation approaches can be found in *Wolf* (2006).

We conclude from our comparison of different approaches to calculate slope length that only the CMA of *Desmet* and *Govers* (1996) consistently implements the concept of the RUSLE and in addition considers irregular slopes. Furthermore this approach is applicable in most standard GIS with additional tools by using MFDAs. As an additional modification we propose to use a catchment size weighted slope length exponent as recommended by *Böhner* et al. (2001; see also *Böhner* and *Selige* 2006). *Desmet* and *Govers* (1996) calculate the local slope length factor L_i with the equation

$$L_i = \frac{\left(A_i + D^2\right)^{m_i+1} - A_i^{m_i+1}}{D^{m_i+2} \times 22.13^{m_i}} \qquad (5)$$

where A_i is the catchment size of slope segment i in m², D the grid resolution in m and m_i the local slope length exponent.

The determination of deposition areas by empirical models is complicated (*Schäuble* 1999; *Wilson* and *Lorang* 1999; *Schmidt* 2001) and few models incorporate it. RUSLE is not able to predict deposition (*Bonilla* et al. 2007) without modifications. Thus, this aspect was not considered in our study and accordingly, we instead estimate a “worst-case” scenario. Furthermore, the relative development of soil erosion due to changes in land cover and its patterns are the main focus of our study and consequently net rates of erosion displacement were less essential. Therefore, it was assumed in our modelling approach that erosion rates were in all instances higher than deposition rates.

2.6 Consideration of flow barriers

Although an empirical model is used to quantify soil erosion, a critical discussion about the process-related consideration of certain parameters to improve modelling results should not be neglected. Land-cover patterns can be considered in soil erosion modelling via the erosive slope length. Changes in land use and land cover affect surface runoff and thereby the suspended soil material. Thus land-cover patterns are a regulating factor of soil erosion, besides the topographic aspects of surface runoff, and it is essential to determine the erosive slope length. The erosive slope length is calculated based on a DEM, for the topographic characteristic, and the land-cover patterns as a characteristic limiting surface runoff. The adequate combination of both inputs is a critical point. In the context of soil erosion, flow barriers from land-cover patterns are elements that affect the surface runoff and consequently the displacement of soil material. Flow barriers can be for instance hedges, tree rows, driveways, roads or simply a change of land cover (e.g., from farmland to grassland or forest and vice versa). Affecting surface runoff, these flow barriers essentially determine the erosive slope length (*Photo 2*). Flow barriers can slow down surface runoff, even stop it (resulting in deposition of material), or they can transmit and accelerate runoff due to convergence, which might increase the energetic transport potential and, in turn, increase soil erosion. For this reason it is crucial to consider how flow barriers are incorporated in modelling surface runoff and soil erosion. So far, in erosion modelling, flow barriers are considered as areas with unlimited infiltration potential (e.g., *Schäuble* 1999; *Schmidt* 2001). This results in the problematic assumption that surface runoff (i.e. mobilised soil material in suspension) is always stopped at flow barriers without any transmission (*Fig. 4a*). However, in reality surface runoff is topography-dependent and stopped or slowed down only when either the inclination of a slope and thus the transport energy is limited (depending on the amount of runoff as well) or a significant change in surface roughness is limiting runoff (and thus leads to deposition of transported soil material in suspension). Hence, erosive slope

Photo 2 Farmland near Pfaffendorf with moderate slope angle and large slope length. Grass, hedges and small trees act as flow barriers and separate agricultural units; here they are, however, parallel to the slope and thus not effective in reducing erosive slope length and soil erosion potential. *Ackerland bei Pfaffendorf mit mäßiger Hangneigung und großer Hanglänge. Fließbarrieren in Form von Gras, Sträuchern und kleinen Bäumen trennen die Ackerschläge voneinander. Durch ihren hangparallelen Verlauf reduzieren diese jedoch nicht die erosive Hanglänge und die Gefahr für Bodenabtrag.*

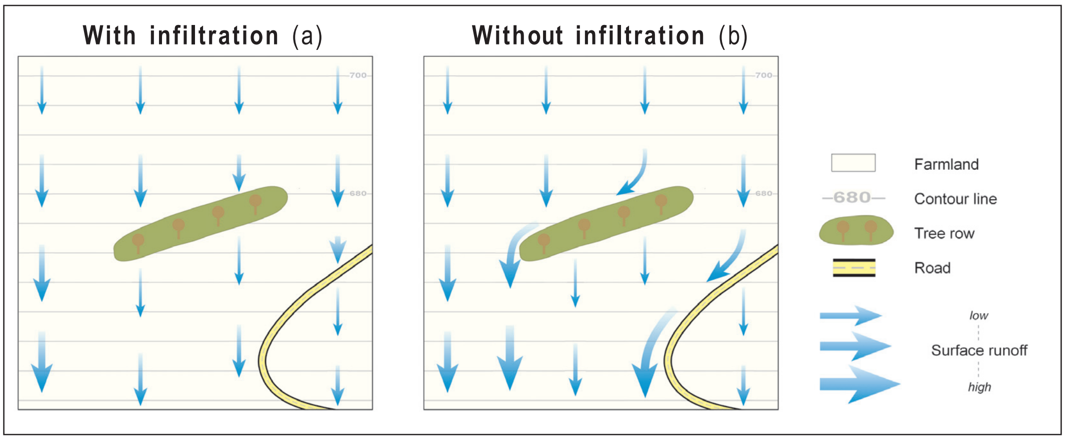

Fig. 4 Illustration of surface runoff in relation to flow barriers. The consequences of the different considerations of flow barriers are shown. With infiltration (a): surface runoff is stopped completely by flow barriers. Without infiltration (b): converging surface runoff along flow barriers and diverging surface runoff downslope leads to higher energetic transport potential and thus higher soil erosion potential. / *Darstellung von Oberflächenabfluss an Fließbarrieren. Dargestellt sind die Auswirkungen einer unterschiedlichen Berücksichtigung von Fließbarrieren. Mit Versickerung (a): Der Oberflächenabfluss wird beim Auftreffen auf Fließbarrieren gestoppt. Ohne Versickerung (b): Konvergierender Oberflächenabfluss entlang von Fließbarrieren und divergierender Abfluss hangabwärts steigern das energetische Transportpotential und verursachen dadurch ein höheres Potential für Bodenerosion.*

length is limited by any flow barrier independently of the topographic situation. Converging effects along, or transmission of surface runoff through, flow barriers are thus neglected. Consequently, the surface runoff uphill from flow barriers has no impact on the downhill areas in this approach of unlimited infiltration. However, these are particularly vulnerable areas as the cumulated surface runoff leads to a greater transport potential and thus larger erosive slope lengths. Therefore we propose to consider flow barriers in surface runoff for erosion modelling without infiltration (*Fig. 4b*). Soil erosion typically occurs during extreme convective precipitation events (like thunderstorms), with strong surface runoff providing the conditions to transport soil material. As the soil surface is then saturated within a short time, the infiltration potential is relatively low and could thus be neglected. We think that our approach represents the process of soil erosion more adequately in empirical models.

In GIS modelling, flow barriers are typically considered with runoff masks and modifications of the DEM. Hence, areas which are marked as flow barriers in the runoff mask are set to NoData in the DEM or considered separately with weighting rasters in the modelling of surface runoff (*Schäuble* 1999). While the first approach results in the explained unlimited infiltration, the application of weighting rasters frequently results in an overflow of flow barriers and thus erroneous modelling results. Therefore, we applied the proposed approach with an artificial exaggeration of flow barriers to realize a topography-related transmission of surface runoff along flow barriers. To avoid cases of overflow on scarps, we recommend exaggerating flow barriers with the maximum elevation occurring in the investigated study area.

Tab. 1 Change of number and size of agricultural units in the investigation area, 1900-1992
Schlagbezogene Entwicklung der Ackerflächen im Untersuchungsgebiet 1900-1992

	1900	**1940**	**1992**
Number of agricultural units	3332	3200	663
Max. size of agricultural units [ha]	42.3	55.7	223.9
Mean size of agricultural units [ha]	2.6	2.5	9.8
Total area of arable land [ha]	8697.7	7958.9	6502.9

3. Results

In order to quantify impacts of changes in land cover and its patterns on soil erosion, we evaluated how arable land developed. The area of arable land decreased by 25 % from 1900 to 1992, covering about 21 % of the National Park Region in 1992 (*Tab. 1*). Few changes in land cover took place in the first half of the 20th century, but after 1940 land reform increased the mean size of agricultural units by nearly 400 %, from 2.6 to 9.8 hectares. Thus, the number of agricultural units decreased significantly from about 3300 to 700 (*Tab. 1*). These changes in land-cover patterns resulted in an increase in erosive slope lengths and consequently a rise in soil erosion potential (*Tab. 2*). In addition to land reform, some arable land was relocated towards siltier soils, areas

Tab. 2 Mean modelling factors and soil erosion displacement
Mittlere Modellierungsfaktoren und Bodenabtrag

	1900	**1940**	**1992**
R-Factor	74	74	74
Change [%]		-	-
K-Factor	0.47	0.48	0.49
Change [%]		***+2.1***	***+2.1***
L-Factor	2.4	2.3	2.5
Change [%]		***-4.2***	***+8.7***
S-Factor	1.3	1.2	0.9
Change [%]		***-7.7***	***-25.0***
LS-Factor	3.7	3.3	2.6
Change [%]		***-10.8***	***-21.2***
Soil erosion [t/ha/a]	117.5	108.4	91.2
Change [%]		***-7.7***	***-15.9***

Tab. 3 Mean soil erosion on continuously-used farmland due to changes in land-cover patterns
Mittlerer Bodenabtrag durch Veränderungen der Landnutzungsstruktur auf kontinuierlich genutzten Ackerflächen

	1900	**1940**	**1992**
Soil erosion [t/ha/a]	79.5	79.4	87.9
Change [%]		***-0.1***	***+10.7***

more vulnerable to soil erosion. In contrast, agricultural use of steep slopes >10° was gradually reduced since 1900, which reduced the S-Factor and, thus, soil erosion potential. Obviously, the latter is able to compensate for the changes in the former, as modelled mean soil erosion decreased by 22 % from 1900 to 1992 with most of this decrease occurring after 1940 (*Tab. 2*), exactly in the same period when erosive slope length increased most significantly due to changes in land-cover patterns. However, as the slope angle is also included in assessing the L-factor (via slope length exponent m) an increase in slope length may be counterbalanced. Mean erosion values are mainly driven by the withdrawal of agriculture from steep slopes. However, we wanted to reach beyond such net effects. Therefore, we attempted to separate changes in soil erosion due to changes in land-cover patterns from spatial relocation and the conversion to other land-cover types by restricting ourselves to areas which had been continuously used as arable land from 1900 to 1992 (determined by spatial intersection with GIS). Thus, we were able to separate and analyse independently slope-length-related changes of land-cover patterns. The results are decisively different from those sketched above (*Tab. 3*). After a slight decrease from 1900 to 1940, mean soil erosion displacement on continuously farmed land increased by almost 11 %. In total, soil erosion increased from 1900 to 1992 on 41 % of the continuously farmed land *(Tab. 4, Fig. 5)*. 9 % showed a strong increase. Only 13 % of the agricultural

Tab. 4 Slope-length-induced changes in soil erosion on continuously-used agricultural units
Hanglängenbedingte Veränderungen des Bodenabtrags auf kontinuierlich genutzten Ackerflächen

	Percent of agricultural units		
	1900-1940	1940-1992	**1900-1992**
Strong decrease	2.0	1.6	**1.9**
Decrease	8.9	10.0	**10.8**
No change	79.4	49.2	**46.8**
Increase	8.4	30.2	**31.6**
Strong increase	1.3	9.0	**9.0**
	100	100	**100**

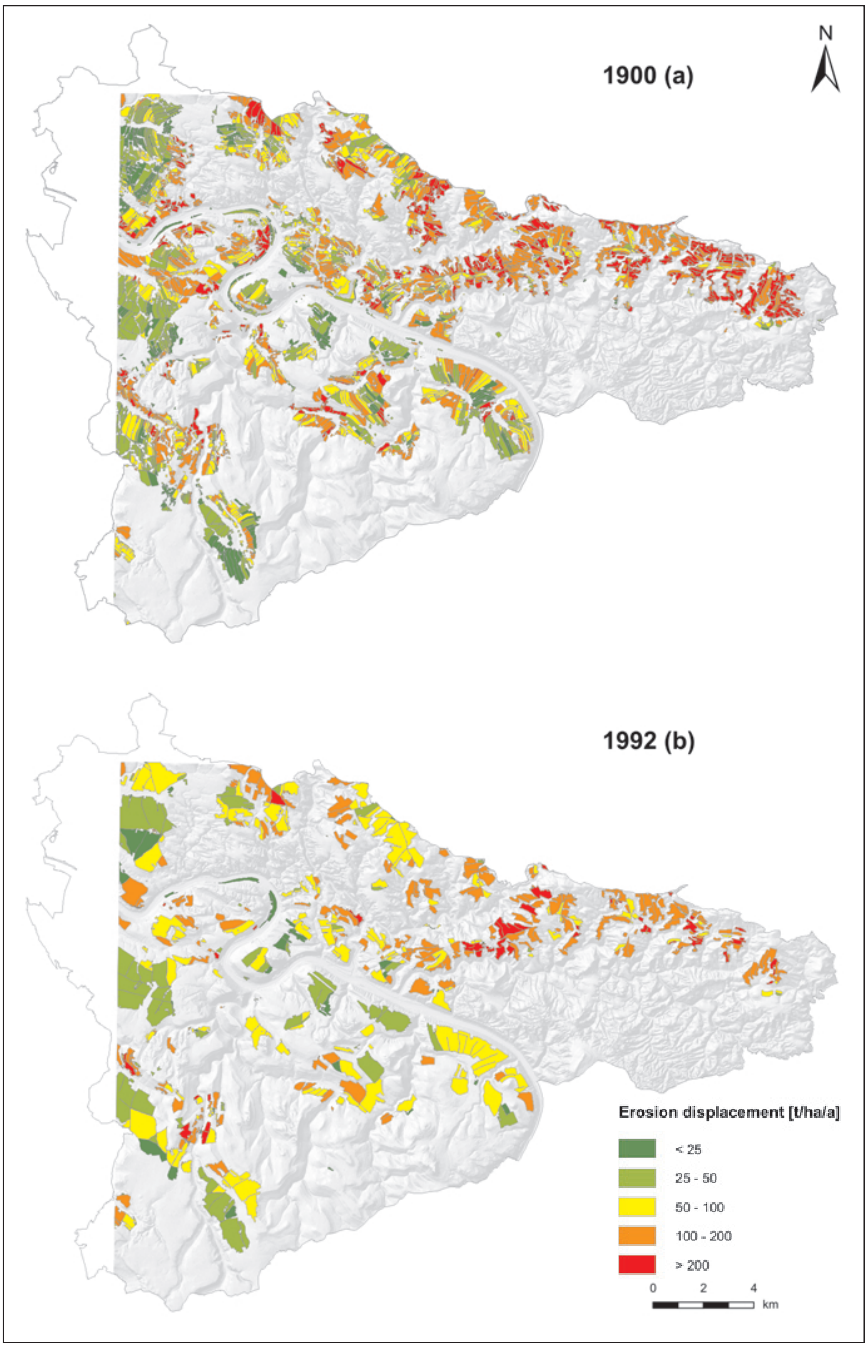

Fig. 5 Soil erosion by agricultural units. Colours indicate soil erosion per agricultural unit; 5 m DEM covers only about 90 % of the study area. / *Schlagbezogener Bodenabtrag. Die Farben kennzeichnen den Bodenabtrag je Ackerschlag; 5 m DGM deckt nur etwa 90 % des Untersuchungsgebietes ab.*

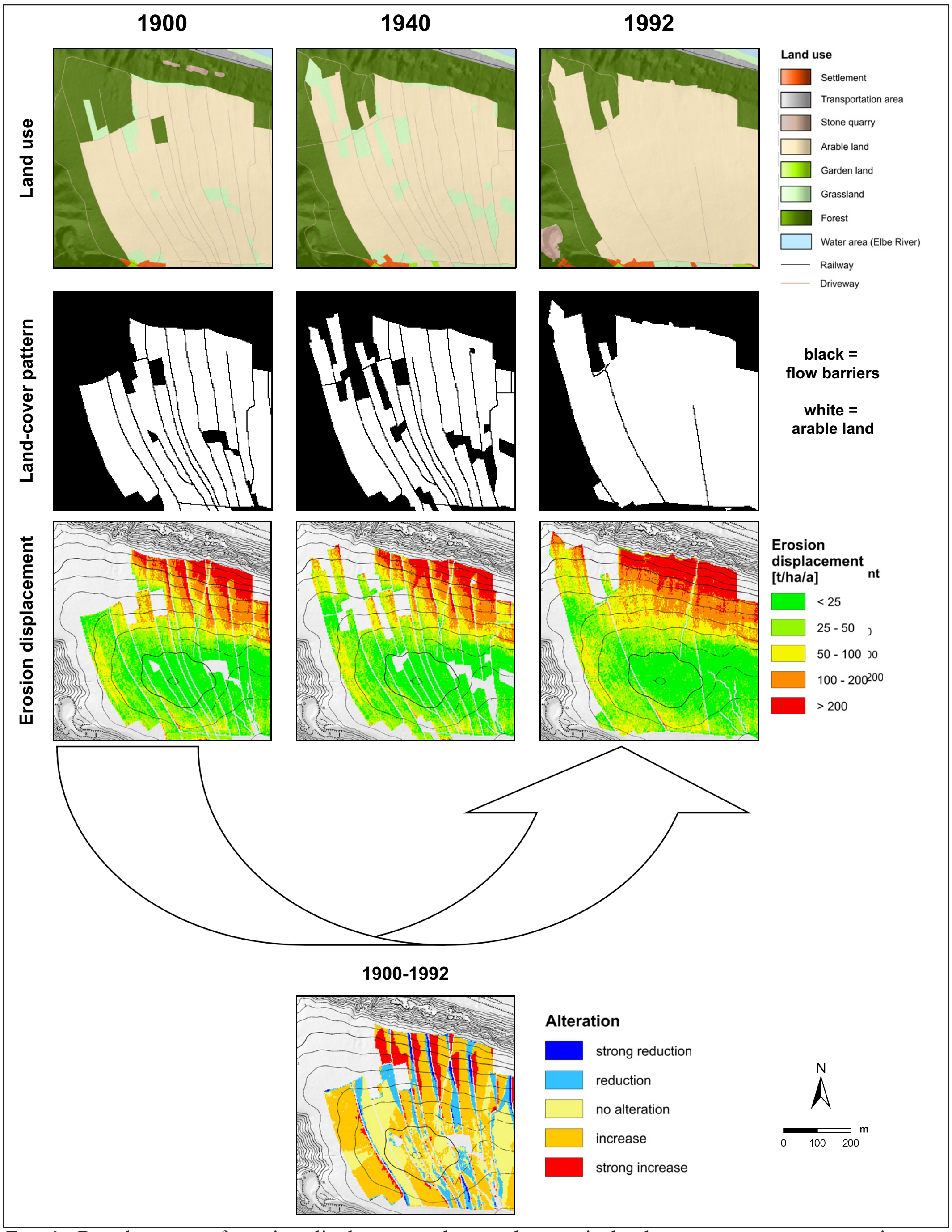

Fig. 6 Development of erosion displacement due to changes in land-cover pattern at a test site near Reinhardtsdorf / *Entwicklung des Bodenabtrags durch Veränderungen der Landnutzungsstruktur in einem Testgebiet bei Reinhardtsdorf*

units observed a decrease in soil erosion from 1900 to 1992, whereas 47 % remained unchanged. Most of the increases are caused by the substantial changes in land-cover patterns after 1940. From 1900 to 1940 almost 80 % of the continuous agricultural units were unaffected by marked changes in soil erosion. Predominantly, areas with enhanced natural erosion vulnerability (mainly steep slopes at plateau rims) were identified as agricultural units with an increase in soil erosion. This is not surprising, as they are particularly sensitive to changes in land-cover patterns.

Several test areas were investigated in greater detail to assess the spatial differences in the study area (e.g., *Fig. 6*), and to document the development of land-cover patterns and soil erosion over the last century. One test area is located near the community of Reinhardtsdorf, on a plateau bordering the Elbe valley (*Fig. 6*). Soil erosion is most intense on foot slopes due to greater slope lengths and slope angles. The effect of convex curvature in combination with high erosive slope length results in high soil erosion rates. In 1900 only driveways perpendicular to the contour lines existed. Some additional driveways along the contour lines had evolved by 1940. Consequently, soil erosion decreased below these driveways (flow barriers) due to a shortening of erosive slope length. With land consolidation and elimination of some driveways after 1940, soil erosion increased on more than 60 % of the farmland. Newly developed agricultural units located in the north-western part of the area have only low slope angles. Thus, even large erosive slope lengths cannot be translated into high kinetic energy and result in moderate soil erosion rates only.

4. Discussion

Utilising the widely used and relatively easily applied RUSLE brings along the limitations of an empirical model (cf. e.g., *Schmidt* 1998; *Michael* 2000). Consequently, we regard results from soil erosion modelling with RUSLE as an approximation of long-term soil erosion, at best. Yet, to approximate the complex process of soil erosion adequately, empirical models can be improved by including physically-based approaches. Approaches proposed in this study are the consideration of flow barriers and the inclusion of the effects of land-cover patterns. Standard GIS and open source software with tools and extensions (e.g. HydroTools, TauDEM) provide the functionality to implement this approach without the need for additional data. The basis for this data is critical for this approach, particularly when using historical maps. Carefully assessing the quality of these historical maps is imperative. The main problem we experienced with historical maps used in our case study are location discrepancies compared to the DEM. In boundary areas of land cover, this resulted occasionally in small areas of arable land being virtually located on very steep slopes (>15°; see AG Boden 2005). It is questionable in general whether some of the agricultural units are really located on very steep slopes or whether this is due to classification errors of mapping.

Due to the interrelation of RUSLE factors (e.g. S- and L-factors), certain effects (e.g. slope angle) have a much greater influence on modelled soil erosion than other factors and, thus, have more weight within the model (*Schwertmann* et al. 1987). This fact is crucial to the interpretation of RUSLE-based model results, because soil erosion can only take place if combined slope angle and slope length provide a critical amount of kinetic energy to displace soil material.

Our results indicate a considerable effect of changed land-cover patterns on soil erosion. We suggest that this finding is applicable beyond the boundaries of the Saxon Switzerland National Park Region, because land reform was introduced in other regions in Germany after

1940 as well (e.g., *Halke* 2002; *Thormann* 2002). Areas with high natural erosion vulnerability were affected most by changes in land-cover patterns, and areas with similar environmental conditions may have experienced comparable evolution of soil erosion. Consequently, we assume that changes in land-cover patterns in the second half of the 20^{th} century have less severely affected typical low-angle agricultural regions, because effects of increased erosive slope length were limited there.

Land-cover pattern is an important factor affecting soil erosion. Thus, we suggest its study is a new and realistic approach to assess historical changes in soil erosion.

Furthermore, we suggest our approach may help identifying future erosion risks under changing environmental conditions. Climate change, for instance, bears the potential for shifts in land use to adapt to altered climatic conditions (*O'Neal* et al. 2005). Farming adaptations (e.g., changed crop types, shifted planting, cultivation and harvest dates) will presumably change the susceptibility of soil to erosive forces (*Southworth* et al. 2000; *Pfeifer* and *Habeck* 2002; *Kundzewicz* et al. 2007). For example, *O'Neal* et al. (2005) suggest that future land-use changes will increase erosion, largely due to a general shift from wheat and maize to soybean, although other scenarios of land-use changes lead to different results mainly because improved conservation practices are assumed (*Souchere* et al. 2005; *Kundzewicz* et al. 2007).

5. Conclusions

Our study suggests that changes in land-cover patterns affect soil erosion due to changes in erosive slope length. Thus, assessing soil erosion should include the investigation of land-cover patterns to properly calculate erosive slope length. Using average slope lengths may lead to an underestimation of soil erosion. In particular flow barriers need to be considered.

Our case study in the Saxon Switzerland National Park Region revealed that the aggregation of agricultural units in the second half of the last century resulted in an increase of erosive slope lengths and thus soil erosion. At the same time agriculture entirely retreated from steep slopes, reducing average soil erosion. Consequently, modelling average soil erosion over larger areas does not necessarily display the effects of increasing erosive slope lengths and may result in misinterpretation. Thus, causes of changes in soil erosion should be assessed in detail in regard to spatial patterns. Our approach to assess historical changes of soil erosion may be of use in simulating developments in soil erosion due to expected changes in environmental conditions (e.g., climate change) or land-use policies. Based on these simulations, optimisation of land-cover patterns appears possible and should be considered in planning decisions which aim at supporting sustainable development and minimising hazardous anthropogenic soil erosion in the future.

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Summary: Effects of Land-Cover Change on Soil Erosion in the Saxon Switzerland National Park Region

Changes in land cover and its patterns affect lateral processes like surface runoff and consequently soil erosion. However, the effects of changes in land-cover patterns are usually not included when modelling soil erosion. Therefore, the effects of land-use and land-cover changes on soil erosion are underestimated. Using an empirical modelling approach based on the Revised Universal Soil Loss Equation (RUSLE), a methodology is proposed to include changes in land-cover patterns in soil erosion models. An assessment of existing approaches to calculate erosive slope length is included. In addition, an improved method for the consideration of flow barriers without infiltration is suggested in order to model surface runoff more accurately according to the process of soil erosion. A case study on soil erosion in the Saxon Switzerland ("*Sächsische Schweiz*") National Park Region, Germany, from 1900 to 1992, confirmed our hypothesis that changes in land-cover patterns considerably affect erosive slope length and accordingly soil erosion. While soil erosion decreased on average over the whole area as agricultural use of steep slopes was reduced, other changes in land-cover patterns caused an increase of soil erosion. From 1900 to 1992 soil erosion increased on 41 % of the agricultural units in the study area due to changing land-cover patterns. This increase primarily occurred after 1940, in conjunction with land reform and the aggregation of agricultural units resulting in longer slopes. Areas with a high Natural Erosion Vulnerability emerged as particularly sensitive to changes in land-cover patterns. Overall, our results suggest that the effects of land-cover patterns on soil erosion have been underestimated so far and need to be considered more precisely in empirical soil erosion modelling.

Zusammenfassung: Auswirkungen von Landnutzungsänderungen auf die Bodenerosion in der Nationalparkregion Sächsische Schweiz

Veränderungen in der Landnutzung und Landnutzungsstruktur beeinflussen Prozesse wie den Oberflächenabfluss und folglich die Bodenerosion. Dennoch werden die Auswirkungen von Veränderungen der Landnutzungsstruktur im Allgemeinen nicht bei der Modellierung der Bodenerosion berücksichtigt. Dadurch werden die Folgen von Landnutzungsänderungen auf die Bodenerosion unterschätzt. Mit der Anwendung eines empirischen Modellierungsansatzes, basierend auf der verbesserten Allgemeinen Bodenabtragsgleichung (RUSLE), wird ein Ansatz vorgeschlagen, welcher Veränderungen in der Landnutzungsstruktur mit berücksichtigt. Zudem wird ein Vergleich von bestehenden Verfahren zur Berechnung der erosiven Hanglänge durchgeführt. Ferner wird eine verbesserte Berücksichtigung von Fließbarrieren ohne Versickerung vorgeschlagen, um Oberflächenabfluss genauer entsprechend dem Prozess der Bodenerosion zu modellieren. Die Anwendung der Methode am Beispiel einer Fallstudie für die Nationalparkregion Sächsische Schweiz (Deutschland) von 1900 bis 1992 bestätigt die Hypothese, dass Veränderungen der Landnutzungsstruktur die erosive Hanglänge und somit die Bodenerosion entscheidend beeinflussen. Während die Bodenerosion durch den Rückzug von Ackerflächen aus steilen Hangpositionen im Durchschnitt für das gesamte Untersuchungsgebiet abgenommen hat, haben Veränderungen in der Landnutzungsstruktur ein Ansteigen der Bodenerosion verursacht. Von 1900 bis 1992 hat die Bodenerosion durch Veränderungen in der Landnutzungsstruktur auf 41 % der Ackerflächen zugenommen. Insbesondere nach 1940 ist die Bodenerosion durch flurbereinigende Maßnahmen und den Zusammenschluss der Bauern in landwirtschaftlichen Produktionsgenossenschaften angestiegen. Flächen mit einer hohen natürlichen Erosionsgefährdung haben dabei besonders empfindlich auf Veränderungen in der Landnutzungsstruktur reagiert. Insgesamt zeigen unsere Ergebnisse, dass die Auswirkungen von Veränderungen der Landnutzungsstruktur auf die Bodenerosion bisher unterschätzt wurden und in der empirischen Modellierung der Bodenerosion genauer berücksichtigt werden müssen.

Résumé: L'influence de l'utilisation des terres sur l'érosion du sol dans la région du parc national de la « Suisse saxonne »

Les changements dans l'utilisation et la distribution spatiale des terres influencent directement le processus du drainage superficiel et donc l'érosion du sol. Néanmoins, les effets de ces changements ne sont généralement pas pris en compte dans la modélisation numérique de l'érosion du sol. Ainsi, l'importance des processus liés à l'utilisation des terres est sous-estimée dans ces modèles. Dans ce papier nous proposons une méthode empirique basée sur l'algorithme RUSLE (équation générale pour l'érosion du sol) qui tient compte des changements d'utilisation des terres pour la modélisation de l'érosion des sols. De plus, cette méthode inclut une évaluation des approches existantes pour calculer la longueur érosive d'une pente. Cette méthode prend également en compte le rôle des barrières de flux qui limitent l'infiltration pour mieux anticiper les processus d'érosion des sols. Une étude de cas réalisée dans la région du parc national de la « Suisse saxonne » (Allemagne) pour la période 1900 à 1992 confirme notre hypothèse selon laquelle les changements d'utilisation des sols modifient considérablement la longueur des pentes sujettes à l'érosion et donc l'érosion des sols. Alors que l'érosion diminue lorsque l'utilisation agricole des terres diminue sur les pentes raides, d'autres changements dans la couverture terrestre ont pu augmenté l'érosion. L'érosion à augmenté de 41 % en moyenne sur les terres arables entre 1900 et 1992 à cause des changements de l'utilisation des terres. En particulier, l'érosion à augmenté après 1940 à cause de la réorganisation des paysans en coopératives agricoles de production et le besoin d'intensifier la production sur de plus grandes unités et donc plus grandes pentes. Les zones de Grande Vulnérabilité à l'Erosion sont d'autant plus sensibles aux changements d'utilisation des terres. En général, nos résultats indiquent que les effets des changements de l'utilisation des terres sur l'érosion du sol ont été sousestimés jusqu'à présent et que ces phénomènes doivent être intégrés de façon plus précise dans la modélisation empirique de l'érosion du sol.

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