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Reassessment of the potential risk of soil erosion by water on agricultural land in Germany: Setting the stage for site-appropriate decision-making in soil and water resources management

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ABSTRACT

Accelerated soil erosion by water on agricultural land is considered one of the most critical forms of soil degradation, as it threatens both agronomic productivity and environmental quality. Given that both the costs and the benefits of soil erosion control measures are subject to spatial variation, the criterion of cost-effectiveness calls for spatially heterogeneous soil conservation policies. Under the German Direct Payments Regulation, federal state authorities are obliged to assess the potential risk of soil erosion by water on arable land in accordance with ABAG – the German version of the well-established Universal Soil Loss Equation (USLE) – and to impose appropriate management restrictions on farmers. However, the responsible federal state authorities have considerable degrees of freedom with regard to the methodology of erosion modelling - and thus in the designation of soil erosion protection areas: First, classification is carried out by multiplication of soil erodibility (K) and slope steepness (S) factors; the inclusion of rainfall erosivity (R) and slope length (L) factors is only optional. Second, classification of RKS- and RKLS-factors corresponds to the assumption of cross-regional standard estimates for R and L, which do not adequately reflect the heterogeneity of local conditions. This inevitably leads to over- and underestimation of local soil erosion hazards. As a consequence, the official risk assessment of soil erosion by water in Germany consists of a patchwork of cadastral risk maps at federal state level, which are neither publicly available nor fully comparable with each other. Hence, under current legislation there is a great danger that management requirements will be imposed on German farmers, which are economically inefficient, distort competition and do not achieve their environmental objectives. The aim of this study is to identify methodological and conceptual potential for improvement and harmonization in the risk assessment of soil erosion by water in Germany. For this purpose, high-resolution nationwide maps of rainfall erosivity (R-factor), soil erodibility (K-factor), slope length (L-factor), and slope steepness (S-factor) are produced in accordance with the revised ABAG using High Performance Computing (HPC) resources. The study area covers arable land, permanent grassland, vineyards, and orchard plantations. The modelling shows that the potential risk of soil erosion by water on agricultural land in Germany is much higher than previously assumed.

1. Introduction

Accelerated soil erosion by water is considered one of the most critical forms of soil degradation (FAO, 2015; IPBES, 2018). On-site, soil loss by erosion can be a major threat to soil quality and agronomic productivity and hence jeopardizes long-term food supply security (Panagos et al., 2018; Bakker et al., 2007). The off-site impacts of soil erosion, in particular the eutrophication of water bodies, the sedimentation of rivers, the loss of water reservoir capacity, and the muddy flooding of public infrastructure and private properties are increasingly being recognized (EASAC, 2018; Boardman et al., 2009). The reduction of soil loss from agricultural land is crucial for the successful implementation of binding environmental agreements: According to the Water Framework Directive (WFD) of the European Union (EU), the EU Member States are obliged to ensure that all surface water bodies achieve "good ecological status" and "good chemical status" by 2015 and in exceptional cases by 2027 (EP and CEU, 2014). In Germany, the achievement of this objective is threatened by high nutrient, heavy metal and pollutant inputs from point and non-point sources into surface waters – whereby soil erosion from agricultural land is one of the most important input pathways (Fuchs et al., 2017; UBA, 2017; Becker and Theis, 2017; UBA, 2018).

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The magnitude of soil loss caused by erosion and the extent of the resulting environmental damage are determined by a combination of heterogeneous natural, land use and management factors. Agricultural land is particularly prone to soil erosion: Intensive tillage, sowing, the cultivation of row and special crops as well as the use of herbicides lead to temporarily vegetation-free soils which are unprotected from the erosive forces of wind and water. According to Cerdan et al. (2010), the average rate of soil loss by sheet and rill erosion for the part of Europe covered by the CORINE database is 1.2 Mg ha^{-1} a^{-1}, but 3.6 Mg ha^{-1} a^{-1} for arable land, respectively. From today's perspective, this forecast can be regarded as conservative, as the influence of extreme precipitation events, which are increasing in the course of climate change, could not yet be taken into account (Auerswald et al., 2019). Findings from Borrelli et al. (2018) indicate that some 15% of gross on-site erosion by water in Europe is transferred to the riverine system - the greatest amount of gross on-site erosion as well as soil loss to rivers is due to agriculture.

Fortunately, under Central European conditions, farmers are well able to effectively contain soil erosion damage through appropriate countermeasures, e.g. reduced or zero tillage, contour ploughing, mulching, cover- and inter-cropping, buffer strips, and sediment traps – among many others (Morgan, 2009; Deumlich et al., 2006a). However – always depending on the individual farms' machinery and equipment, the professional skills and the natural site conditions – the costs of many soil erosion control measures exceed the on-site benefits (Kuhlman et al., 2010; Posthumus et al., 2013). Thus, many farmers are reluctant to implement ambitious soil erosion control measures without additional monetary incentives (Lahmar, 2010; Auerswald et al., 2018).

Apparently – as Panagos et al. (2016) put it – soil loss does not occur because of any lack of knowledge on how to protect soils, but a lack in policy governance. Since both the costs and the benefits of soil erosion control measures are subject to spatial variation, the criterion of cost-effectiveness calls for spatially heterogeneous conservation policies (Fleming and Adams, 1997; Carpentier et al., 1998; Kuhlman et al., 2010; Deumlich et al., 2006b). This requires the identification and delineation of priority areas where soils are particularly vulnerable to erosion and hence benefit disproportionately from soil conservation (Panagos et al., 2016). Furthermore, properly designed modelling assumptions on potential soil erosion risk are a key pre-requisite for assessing the impact of land use and management on actual on-site erosion, sediment transport, carbon, nutrient, and pollutant fluxes (Borrelli et al., 2018) as well as their respective environmental and welfare repercussions (Posthumus et al., 2013). Accordingly, the demand for instructive geospatial information about site-specific soil erosion hazards has greatly increased both on regional, national and international policy levels (Prasuhn et al., 2013; Bosco et al., 2015).

Coherent soil and water protection planning requires harmonized and precise spatial information on local soil erosion risk. Within the framework of the Common Agricultural Policy (CAP) of the European Union, farmers are obliged to cross-compliance (CC). It is the aim of CC to establish basic regulatory standards that all farmers must meet in order to receive CAP payments. To ensure that all agricultural land is maintained in good agricultural and environmental conditions (GAEC), EU member states shall define minimum requirements on the basis of Annex II of Council Regulation (EC) No 1306/2013. In this context, under GAEC 5 (*minimum land management reflecting site specific conditions to limit erosion*), risk-assessment procedures have to be introduced on national or regional level to help farmers identify sites where soil erosion control measures are required (Boardman et al., 2009). Under the German Direct Payments Regulation (*Agrarzahlungen-Verpflichtungen-Verordnung*, DPR) (BMEL, 2017), federal state authorities are obliged to classify arable land with respect to the risk of soil erosion according to the standard DIN 19708 (2017) and to impose appropriate management restrictions. The conceptual and technical prerequisites for a nationwide uniform classification of soil erosion risk have been in place for decades (Flacke et al., 1990; Auerswald et al., 1988). However, under the statutory provisions of the German DPR, the federal state authorities have some substantial degrees of freedom with regard to the methodology of erosion modelling - and hence in the designation of soil erosion protection areas (Tetzlaff et al., 2013; Brandhuber, 2010; Schäfer et al., 2017; Sauer and Goldschmitt, 2010; Elhaus, 2010). A majority of seven federal states classifies the soil erosion risk by water according to *DIN 19708* as a product of the R-, K-, and S-factors. Another 5 federal states restrict on the multiplication of K and S, and only the small federal state *Saarland* includes the L-factor. The digital soil maps and the related databases used by the federal states are methodologically inconsistent (Krug et al., 2013) and are generally not freely available for external scientific purposes. Moreover, different precipitation data and different derivation rules are used at the federal state level to estimate rainfall erosivity. The differences in the approaches may be well justified from a technical point of view or result from limited data availability. However, it is impossible to compare and integrate the different products.

On the basis of surrogate geodata, e.g. Wurbs and Steininger (2011), Saggau et al. (2017), Auerswald et al. (2009) and the BGR (2014) have compiled methodologically sound nationwide maps of soil erosion risk in Germany. However, due to a recent update of the German Standard DIN 19708 (2017) on the prediction of soil erosion by water, due to a novel approach to derive rain erosivity from contiguous radar rain data (Auerswald et al., 2019) and due to the availability of new high-resolution topography, land-use, and soil information geodata, a substantial revision of existing products is overdue. For these reasons, this paper aims to reassess the potential risk of sheet and rill erosion on agricultural land in Germany using ABAG (Schwertmann et al., 1990), the German version of the *Universal Soil Loss Equation* (USLE) (Wischmeier and Smith, 1978). To this end, raster maps (10·10 m) of soil erodibility (K-factor), slope steepness (S-factor) and slope length (L-factor) are provided. In conjunction with a freely available map of rain erosivity (R-factor) in Germany (Auerswald et al., 2019), these maps may serve as a basis for assessing and further improving the cost-effectiveness of current soil and water protection legislation in Germany.

2. Material and methods

2.1. ABAG-modelling of soil erosion by water

Soil erosion by water is a complex process that is related to partly interacting soil, climate, topography, and vegetation conditions, as well as human activities. Due to the high spatial and temporal heterogeneity of the causal variables, the on-site measurement and monitoring of soil loss rates at larger spatial scales is financially infeasible. Thus, many soil erosion models were developed to assess regional soil erosion hazards and optimize precautionary soil conservation management (Lal, 2001; Boardman, 2006). Due to minimal data and computation requirements and a practicable model structure, the USLE remains the most widely used model to predict soil erosion by water. The *Revised Universal Soil Loss Equation* (RUSLE) (Renard et al., 1997; USDA, 2013) and national USLE derivates (e.g. ABAG) have replaced USLE in most applications today, but the basic formula remains the same. (R)USLE and ABAG assess the long-term average annual soil loss resulting from raindrop splash and runoff according to the equation:

$$E = R \bullet K \bullet L \bullet S \bullet C \bullet P \tag{1}$$

with E = long-term average annual soil erosion by water [Mg/(ha·a)];

R = rainfall-runoff erosivity factor [N/(h·a)];
K = soil erodibility factor [(Mg·h)/(ha·N)];
L = slope length factor [dimensionless];
S = slope steepness factor [dimensionless];
C = cover-management factor [dimensionless];
P = support practice factor [dimensionless].

One decisive advantage of (R)USLE and ABAG is their modular design: Every combination of independent variables provides meaningful information about the risk of soil erosion on the respective level of integration. For instance, the risk of soil erosion by water can be divided into a *potential* and *actual* risk (Wurbs and Steininger, 2011; Prasuhn et al., 2013; van Rompaey et al., 2001). In accordance with *DIN 19708*, the natural sensitivity of soils to erosion by water - irrespective of land use, vegetation cover and management practices - is hereinafter referred to as the *potential risk of soil erosion* (E_{pot}). Note that E_{pot} is a hypothetical parameter, which assumes that the soil surface is vegetation-free and no soil protection measures are applied (van Rompaey et al., 2001). In erosion modelling, however, it is quite common to combine the slope length factor (L) and the slope steepness factor (S) as they conjointly describe the effect of topography on soil erosion by water (Panagos et al., 2015b; USDA, 2013). Accordingly, many studies include the L-factor to assess the potential risk of soil erosion by water (Prasuhn et al., 2013). Technically speaking, the slope length of agricultural plots is not natural and unchangeable but can be altered actively by land consolidation and plot realignment measures, the planting of hedgerows, the trenching of ditches, etc. (Liu et al., 2013; Mihara, 1996; van Oost et al., 2000; Morgan, 2009). In practice, however, the individual farmer's scope for action is usually limited to agricultural land in permanent ownership. In Germany, the share of leased agricultural land is currently around 59 percent (Destatis, 2017); for historical reasons, the size of agricultural plots varies greatly from region to region. Against this background, it would therefore appear appropriate to include the L-factor in the assessment of the potential risk of soil erosion. In this study, the influence of the R-, K-, L- and S factors on the erosion classification will be investigated.

Classification of KS-, RKS-, and RKLS-factors is carried out following the German DPR (BMEL, 2017) and DIN 19708 (2017) (Table 1). DIN 19708 only makes a classification based on the combined RKS factors to assess the potential risk of soil erosion. In order to be able to make risk classifications on the basis of KS- and RKLS-factors as well, the German DPR introduced highly simplified assumptions about rainfall-runoff erosivity (default R-factor = 50) and slope length (default L-factor = 2) on arable land in Germany. These assumptions are critically discussed in chapter 4.

Each ABAG factor is mapped in a geographic information system (GIS) by a grid of equal-sized 10 m·10 m raster cells. These raster maps can be multiplied with each other to calculate the *potential* risk of soil erosion by water. Grids are aligned to the extent of the *Digital Terrain Model Grid Width 10 m* (DGM 10) (see Section 2.5), provided by the *Federal Institute for Cartography and Geodesy* (*BKG*). Open source GIS software QGIS (version 3.12.1)[1], GRASS GIS (version 7.8.2)[2] and SAGA GIS (version 7.0.0)[3] and open source software for statistical computing R (version 3.6.3)[4] are used to provide a consolidated, verifiable and repeatable procedure for erosion risk assessments. The memory intensive calculation of slope gradients, the identification of surface depressions, and the modelling of field-based L-factors are performed using High Performance Computing (HPC) resources of the GWDG[5]. A detailed description of methods, the R-scripts and HPC Bash shell scripts are provided in the supplementary material.

2.2. Study area

The study area covers about 19.1 million ha, which corresponds to the agricultural land in Germany as per definition of the *Digital Land Cover Model for Germany* (LBM-DE 2015)[6]. On behalf of the Federal Environment Agency (UBA), the BKG compiles the national contribution to the European CORINE Land Cover (CLC)[7] data set on the basis of the LBM-DE. In contrast to the cross-national CLC, the minimum mapping unit of LBM-DE is 1 ha and the minimum mapping width is 15 m. This allows a more detailed spatial differentiation of the individual land cover units.

According to rasterized LBM-DE 2015 data, agricultural land in Germany comprises some 12.34 million ha of non-irrigated arable land (CLC nomenclature 2.1.1), 0.12 million ha of vineyards (CLC 2.2.1), 0.23 million ha of fruit trees and berry plantations (CLC 2.2.2) and 6.45 million ha of permanent pastures (CLC 2.3.1)[8].

Table 1
Risk classification of soil erosion by water according to the legal requirements of the German DPR (KS and RKLS) and DIN 19708 (RKS). Values in Mg ha^{-1} a^{-1}.

Class	Description	R·K·S	K·S	R·K·S·L
$E_{pot}0$	no or very low risk of soil erosion	< 0.5	*< 0.01*	*< 1.0*
$E_{pot}1$	very low risk of soil erosion	0.5– < 2.5	*0.01– < 0.05*	*1.0– < 5.0*
$E_{pot}2$	low risk of soil erosion	2.5– < 5.0	*0.05– < 0.1*	*5.0– < 10.0*
$E_{pot}3$	medium risk of soil erosion	5.0– < 7.5	*0.1– < 0.15*	*10.0– < 15.0*
$E_{pot}4$	high risk of soil erosion	7.5– < 15.0	*0.15– < 0.3*	*15.0– < 30.0*
$E_{pot}5$	very high risk of soil erosion	15.0– < 27.5	0.3– < 0.55	30.0– < 55.0
$E_{pot}6$	extremely high risk of soil erosion	≥27.5	≥0.55	≥55.0

Italic type: KS- and RKLS-classes $E_{pot}0$–$E_{pot}4$ are derived from classes $E_{pot}5$ and $E_{pot}6$ according to the assumptions on default R- and L-factors in the German DPR.

2.3. R-factor (rainfall-runoff erosivity)

The ability of rain to cause soil erosion by detaching particles and generating surface runoff is called rainfall-runoff erosivity. In the (R) USLE and ABAG, rainfall-runoff erosivity is quantified in the R-factor. The R-factor is a multi-annual average index. It measures the kinetic energy and intensity of rainfall events to describe the effect of precipitation on sheet and rill erosion. Originally, the R-factor is derived from an in-depth analysis of individual erosive rainfall events over multiple years. Hence, long-term time series rainfall data with high spatial and temporal resolution are required to accurately determine the R-factor. Since the manual acquisition of appropriate precipitation data on larger spatial scales is expensive and time-consuming, regression equations were developed, which describe the relationship between the R-factor and more readily available precipitation data (Panagos et al., 2015a; Nearing et al., 2017). In Germany, for example, *DIN 19708* lists a total of 26 regression equations, which illustrate the regional relationship between the multiannual summer/annual sum of precipitiation and the R-factor. However, this correlation varies greatly from region to region; the correlation coefficient r is between 0.40 in the northern German federal state of Mecklenburg-Western Pomerania and 0.96 in the southern German federal state of Bavaria. Moreover, recent studies on climate change in Germany show a marked change of heavy rainfall patterns in Germany, making the previous approach no longer applicable (Elhaus et al., 2019). Against this background,

[1] https://qgis.org, (accessed 2020–03-31).
[2] https://grass.osgeo.org/, (accessed 2020–03-31).
[3] http://www.saga-gis.org/en/index.html, (accessed 2020–03-31).
[4] https://www.r-project.org/ (accessed 2020–03-31).
[5] https://www.gwdg.de/application-services/high-performance-computing, (accessed 2020–03-31).
[6] https://www.bkg.bund.de/DE/Ueber-das-BKG/Geo-information/Fernerkundung/Landbedeckungsmodell/landbedeckungsmodell.html (accessed 2018–09-22).
[7] https://land.copernicus.eu/pan-european/corine-land-cover (accessed 2018–09-22).
[8] Rounded figures. It should be noted that the available maps of land cover derived from remote sensing on the one hand and official statistical information about land use on the other hand are often not fully comparable due to methodological differences (Wiatr et al., 2016).

Auerswald et al. (2019) have used contiguous RADKLIM radar rain data with high spatiotemporal resolution to derive a new R-factor map for Germany. The average annual R-factors calculated for the period 2001 to 2017 show a strong increase in rainfall-runoff erosivity compared to previous evaluations (Auerswald et al., 2019; Elhaus et al., 2019). These new R-factor values are further used in this study.

2.4. K-factor (soil erodibility)

The soil erodibility factor (K-factor) accounts for the influence of soil properties and soil profile characteristics on soil erosion. According to Panagos et al. (2014) and Efthimiou (2018), the lack of sufficient data on soil characteristics is one of the greatest obstacles to soil erosion modelling at larger spatial scales. That also applies to Germany: Up to the present, the only consistent spatial soil database for the whole of Germany has been a small-scaled 1:1.000.000 soil map (BÜK 1000), secondary products (e.g. BÜK 1000N) and related background data (Hartwich et al., 1995). BÜK 1000N was used as a basis for many modelling approaches of soil erodibility in Germany (Wurbs and Steininger, 2011; Saggau et al., 2017; Saggau, 2016; BGR, 2014). As early as the mid-1990s, the *Federal Institute for Geosciences and Natural Resources* (BGR) and the federal *State Geological Surveys of Germany* (SGD) started a programme to compile a medium-scaled digital soil map of Germany and a relational soil database. As a result of this joint project, a total of 55 vector map sheets were published in summer 2018[9], accompanied by a preliminary soil database (current version 0.5)[10]. The vector map sheets and the soil database together form the nationwide *Digital 1:200.000 Soil Map of Germany* (BÜK 200) (Krug et al., 2013).

With the availability of BÜK 200, the data basis for determining K-factors in Germany has improved. The new derivation rules for K-factors, which were introduced in the course of the last revision of *DIN 19708*, are also very important: Originally, the K-factor was either read out from a multivariable K-factor nomogram or derived from a series of K-factor equations, which describe the relationship between the K-factor, and soil texture, soil organic matter content, rock fragment cover, soil aggregation, and permeability (Wischmeier and Smith, 1978). Auerswald and Elhaus (2013) and Auerswald et al. (2014) have exemplified that substituting the USLE nomogram with the classical K-factor equations frequently leads to wrong predictions of the K-factor. They propose a set of new K-factor equations that fully emulate the USLE nomogram and hence supersede the classical K-factor equations. These new rules have been integrated into the updated *DIN 19708*.

For the evaluation of soil maps, the revised *DIN 19708* allows the determination of K-factors in a three-step procedure: Following Auerswald et al. (2014), *DIN 19708* defines average K-factors of 38 individual soil textures as per Sponagel (2005). Subsequently, the average K-factors can be adjusted for the site-specific content of soil organic matter, and the coverage with rock fragment. It should be noted that BÜK 200 does not report the percentages of soil organic matter content and rock fragment cover, but only content classes. In this study, K-factors are therefore determined using simplified derivation rules (BGR, 2020a,b). For details please read the method description.

In QGIS, adjusted K-factors are transferred to the soil mapping units of BÜK 200. It should be noted that these mapping units do not describe individual soils, but regional associations of soils (German: *Bodenvergesellschaftungen*). It is common practice to assign the characteristics of the respective principal soil to a regional association of soils and hence discard the properties of minor associated soils (Hennings, 2000; Wurbs and Steininger, 2011). However, this pragmatic approach does not take adequate account of the heterogeneity of soil and land use characteristics within the regional associations of soils. Fortunately, the BÜK 200 soil database reports both on dominant land use characteristics of individual soils (e.g. arable land, permanent grassland, specialized crops, etc.) and on the spatial proportion of principal and associated soils in the respective legend unit. This enables a relational weighting of individual soils' K-factors within the respective regional associations of soils (Krug et al., 2010). In order to provide adequate K-factors for arable land, permanent grassland, vineyards, as well as fruit trees and berry plantations, three corresponding K-factor raster maps are derived from BÜK 200. For details please read the method description.

As already mentioned, the soil database of BÜK 200 is provisional and still incomplete. Especially from the Free States of Saxony and Bavaria there is a lack of information about soil properties, which are needed for a calculation of the K-factors according to the presented method. Soils for which no information is currently available in BÜK 200 are therefore analysed on the basis of BÜK 1000N. This applies to about 17% (some 3.3 million ha) of the study area.

2.5. S-factor (slope steepness)

The S-factor measures the effect of slope steepness on soil erosion by water. The S-factor is one of the most sensitive parameters of the (R) USLE and ABAG. With increasing spatial resolution and accuracy of the digital elevation model (DEM) used, the shape of the landscape is described more accurately and erosion estimates approach actual values (Hickey, 2000). However, high-resolution DEM input data considerably increase computing requirements (Panagos et al., 2015b).

According to *DIN 19708*, the S-Factor is calculated following the equation proposed by Nearing (1997), which is also suitable for steep slopes such as those frequently found on vineyards, orchards and grasslands in Germany (Auerswald et al., 2009). The calculation of S-factors on agricultural land in Germany is based on the *Digital Terrain Model Grid Width 10 m* (DGM 10) (BKG, 2015). Raster width is 10 m·10 m, accuracy in open terrain is about ± 0.5–2.0 m. To generate a slope map from DGM 10, the SAGA-GIS module *Slope, Aspect, Curvature*[11] is executed using the Horn (1981) algorithm.

2.6. L-factor (slope length)

According to the original definition of Wischmeier and Smith (1978), the L-factor describes the ratio of soil loss from a slope of any length to a standard slope of 22.13 m in length. According to the definition of (R)USLE and ABAG, the effective upslope length may be shorter than the total length of a slope. It follows that the effective upslope length usually cannot be derived directly from DEMs or topographic maps. Therefore, from a methodological perspective, slope length calculations are often the most problematic of the erosion model parameters (Hickey, 2000). A makeshift method of calculation is to use a regional or supra-regional standard estimate for effective upslope length - thereby converting a variable into a constant (Hickey, 2000). Under central European conditions, standard upslope lengths of 100 m (Bundesrat, 2008) or 200 m (Auerswald et al., 2009; Saggau et al., 2017) are most commonly used. Likewise, risk classification of RKLS-values according to the German DPR (BMEL, 2017) relates to the assumption of a standard effective upslope length of 100 m (L-factor approx. 2).

Recognizing that real slopes cannot be considered as totally uniform, Foster and Wischmeier (1974) suggest to subdivide slopes into a number of uniform segments (see the analogous procedure in *DIN*

[9] https://www.bgr.bund.de/DE/Themen/Boden/Aktuelles/BUK200-Flaechendeckung.html, (accessed 2018–10-16).

[10] https://produktcenter.bgr.de/terraCatalog/OpenSearch.do?search=154997F4-3C14-4A53-B217-8A7C7509E05F&type=/Query/OpenSearch.do, (accessed 2018–10-20).

[11] http://www.saga-gis.org/saga_tool_doc/2.1.3/ta_morphometry_0.html, (accessed 2019–10-30).

19708 and Renard et al. (1997)). Desmet and Govers (1996), among others, emphasize the importance of adequately capturing two-dimensional terrain features in erosion modeling and suggest to replace the one-dimensional upslope length by a Unit Contributing Area (UCA). UCA is the upslope drainage area per unit of contour length (van Rompaey et al., 2001). Flacke et al. (1990) have taken a similar approach in Germany. With the increasing availability of high-resolution DEMs, the calculation of L-factors in GIS-environments according to the UCA approach was made possible also for large scale erosion modelling approaches - provided that sufficient computer capacities are available. Numerous recent studies on erosion modelling (Panagos et al., 2015b; van Rompaey et al., 2003; van Oost et al., 2000; van Rompaey et al., 2001; Bakker et al., 2008; Prasuhn et al., 2013; Schmidt et al., 2019) have argued for and calculated the L-factor according to Desmet and Govers' (1996) approach.

Against this background, deviating from the German standard *DIN 19708*, the estimation of the L-factor follows the approach introduced by Desmet and Govers (1996) using the powerful SAGA-GIS module "*LS Factor, field-based*"[12] (Panagos et al., 2015b; Panagos et al., 2015c; Schmidt et al., 2019). LS-factors are calculated for each polygon for which an agricultural land use (arable land, permanent pasture, vineyard, fruit and berry plantation) is identified in LBM-DE 2015. It is assumed that the boundaries of these agricultural land cover polygons constitute rigid barriers to downslope runoff. It should be noted that the SAGA-GIS module uses the original RUSLE equations to calculate the S-term (Renard et al., 1997), which are different from the equation according to Nearing (1997). The LS-factors calculated by the SAGA algorithm are therefore divided by RUSLE S-factors to isolate the L-term. For details and model specifications please read the method description.

The identification of surface depressions is a critical, yet computation intensive preprocessing step for the automated modelling of surface rainfall runoff based on DEMs. As per definition of Wang and Liu (2006), a surface depression is a local minimum that does not have a downslope flow path to any adjacent cells in a DEM. It acts as a sink to the surrounding overland flow, in which water drains towards the depression bottom. Within surface depressions, the deposition of eroded sediment exceeds soil detachment. Depressions in DEMs can be real natural landscape features or spurious artefacts. However, natural depressions are rare and far less common than spurious depressions (Wang and Liu, 2006). To obtain a fully connected and consistent drainage system for hydrologic analysis, surface depressions need to be treated before other hydrologic processing steps can be made. The SAGA-GIS module "*Fill Sinks XXL*"[13] was used to efficiently identify surface depressions in DGM 10. The algorithm allows not only to fill these sinks, but also to preserve a downward slope along the flow path. This is accomplished by preserving a minimum slope gradient between raster cells. For details and module specifications please read the method description.

3. Results

3.1. The baseline model: natural risk of soil erosion by water (RKS-factor)

The results of the RKS-calculation are displayed in two variants: Fig. 1 shows the absolute potential soil loss per grid cell. Based on this map, Table 2 shows the percentage of arable land, permanent grassland, vineyards and orchard plantations in Germany that is classified in each of the seven risk categories according to *DIN 19708*.Fig. 2.

In Germany, the potential risk of soil erosion by water (RKS-factor) on agricultural land varies greatly among regions and land uses (Table 2): About 47% of the study area has *no*, *very low*, or *low risk* of soil erosion (< 5.0 Mg ha^{-1} a^{-1}). No less than 29% of the study area has a *very high* or *extremely high risk* of soil erosion (> 15.0 Mg ha^{-1} a^{-1}) and therefore should be subject to management restrictions under the German DPR. The total average (x) of RKS-values on agricultural land in Germany is 16.5 Mg ha^{-1} a^{-1}, standard deviation (sd) is 33.6 Mg ha^{-1} a^{-1}.

In Germany, fertile fine-textured arable soils with high erodibility (e.g. loess soils) and steep slope angles show the highest potential risk of erosion. Accordingly, the arable land in the *Lower Saxon Hills* (1), the *Central Saxon Loess Hill Country* and the *Ore Mountain Foreland* (2), the *Gäu Plateaus* (3), and the *Lower Bavarian Hill Country* (4) are hot spots of potential soil erosion risk in Germany[14]. The fertile loess soils of the *Magdeburg Börde, Hildesheim Börde*, the *Hellweg Börde*, and the *Jülich-Zülpich Börde* feature highest soil erodibility, but they are mostly gently undulating. In the low mountain regions there is also an increased risk of soil erosion on arable land. Here again, soil erodibility is lower, but the slopes are more inclined. The arable land at the *Northern Plain* is generally characterized by a low or very low potential risk of soil erosion. However, there is a moderate and occasionally a high potential risk of soil erosion on arable land in the young drift morainic landscapes in the federal states of *Schleswig-Holstein*, *Mecklenburg-West Pomerania* and *Brandenburg*. The calculated average RKS soil erosion rate on arable land in Germany amounts to 11.5 Mg ha^{-1} a^{-1} (sd = 16.8 Mg ha^{-1} a^{-1}).

Traditionally, the mowing and grazing of permanent grassland has enabled value-adding agricultural activity even on marginal land and land that was difficult to farm. Many meadows and pastures are to be found on steep slopes, in floodplains, and in places where high amounts of precipitation impede the successful cultivation of field crops. Thus the spatial patterns of grassland distribution in Germany to a certain extent reflect the risk of erosion of agricultural soils. Correspondingly, permanent grassland in Germany is to be found on soils with an above-average potential risk of erosion by water ($\bar{x}=24.3$ Mg ha^{-1} a^{-1}; sd = 48.4 Mg ha^{-1} a^{-1}). About half of the permanent pasture area is classified as having a *high*, *very high* or *extremely high* potential risk of soil erosion. More than 1.6 million ha (some 25%) of soils under permanent grassland are exposed to an *extremely high* potential risk.

In Southern Germany, many orchard plantations are to be found at the hill ranges e.g. of the *Upper Rhine Plain,* at the *Gäu Plateaus* and the *Donau-Isar Hill Country*. Due to a combination of steep slopes and highly erodible soils, most plantation areas (approx. 78%) are assigned high erosion risk classes (≥7.5 Mg ha^{-1} a^{-1}). The region *Altes Land,* downstream of *Hamburg* on the southwestern banks of the *Elbe*, is the largest contiguous fruit-growing region in northern Europe. Here, orchard plantations are located on reclaimed marshland with relatively high soil erodibility – but on shallow slopes. Overall, the calculated average potential risk of soil erosion on fruit and berry plantations in Germany amounts to 49.1 Mg ha^{-1} a^{-1} (sd = 73.9 Mg ha^{-1} a^{-1}).

In Germany, favorable climatic and soil conditions have promoted the cultivation of wine in 13 particular regions, six of which are situated in the West German federal state of *Rhineland-Palatinate* along the river *Rhine* and its tributaries. Further important wine-growing districts are located in the federal state of *Baden-Württemberg,* e.g. at the *Upper Rhine Plain* and the *Kaiserstuhl* - a cluster of volcanic hills. Some 86% of German vineyards are classified as having soils of *high*, *very high* or *extremely high* potential risk of soil erosion (≥7.5 Mg ha^{-1} a^{-1}). Almost half of the German vineyard area is extremely endangered by soil erosion (≥27.5 Mg ha^{-1} a^{-1}). The calculated average potential risk of soil erosion for German vineyards is 54.9 Mg ha^{-1} a^{-1}

[12] http://www.saga-gis.org/saga_tool_doc/2.2.1/ta_hydrology_25.html, (accessed 2018–11-30).

[13] http://www.saga-gis.org/saga_tool_doc/2.2.7/ta_preprocessor_5.html, (accessed 2019–01-07).

[14] The hot-spot regions are highlighted in Figure 1. An overview of the natural regions in Germany can be found at https://de.wikipedia.org/wiki/Naturraum (accessed 2020–03-31).

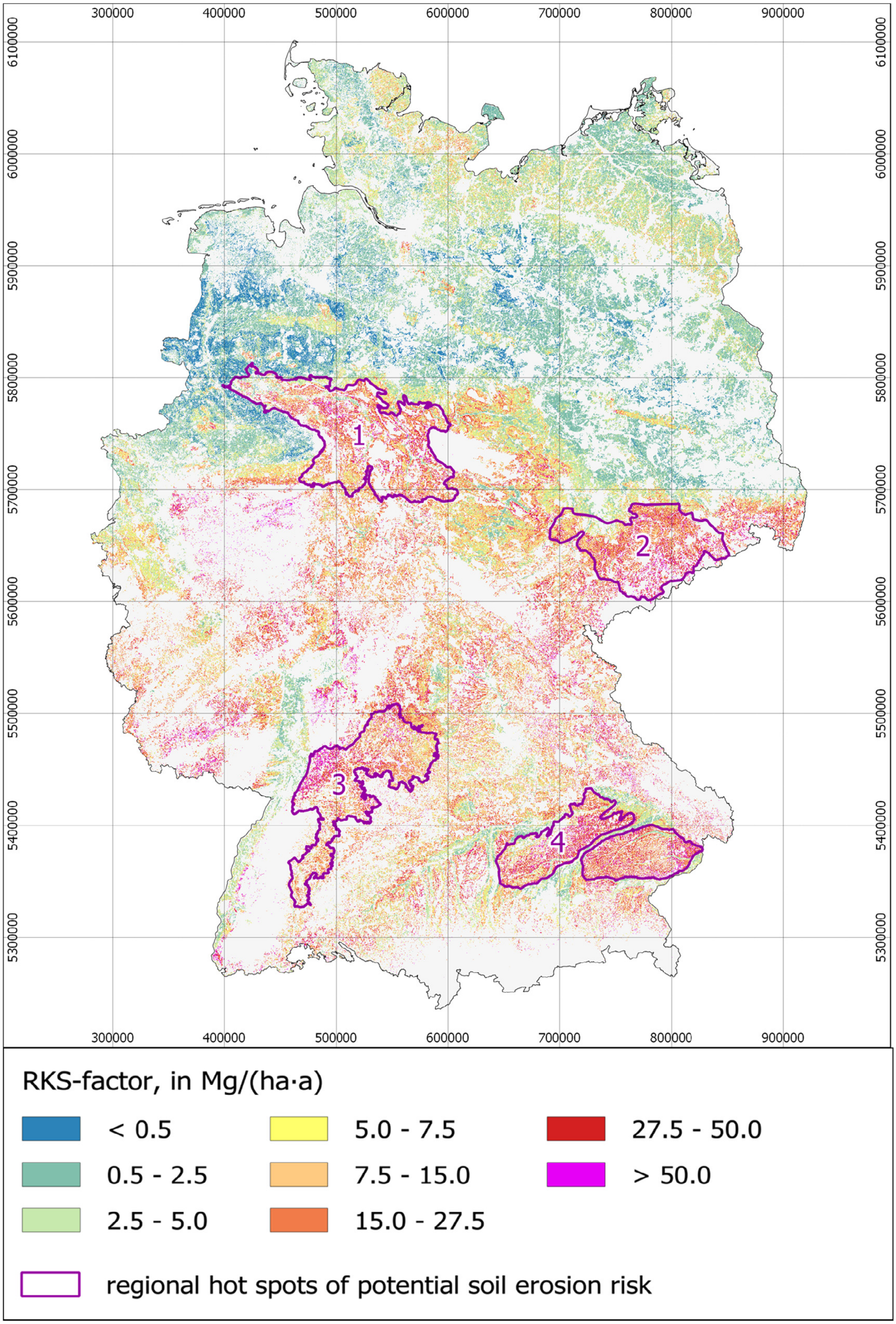

Fig. 1. High-resolution (10 m grid cell) map of potential soil erosion risk (RKS) on arable land in Germany. Maps for permanent grassland, vineyards and fruit-growing can be provided on request.

Table 2
Potential risk of soil erosion by water (RKS-factor, classification according to DIN 19708) on agricultural land in Germany (rounded figures).

Class	Total		Arable land		Grassland		Vineyards		Fruit/berry	
	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%
$E_{pot}0$	1062	6%	669	5%	392	6%	0	0%	1	0%
$E_{pot}1$	4882	26%	3234	26%	1631	25%	2	2%	15	6%
$E_{pot}2$	2978	16%	2190	18%	760	12%	6	5%	22	9%
$E_{pot}3$	1694	9%	1253	10%	419	7%	8	7%	14	6%
$E_{pot}4$	2871	15%	2034	17%	783	12%	21	18%	32	14%
$E_{pot}5$	2363	12%	1517	12%	785	12%	23	20%	37	16%
$E_{pot}6$	3214	17%	1415	11%	1631	25%	58	49%	110	48%
Σ	19063	100%	12313	100%	6401	100%	119	100%	230	100%

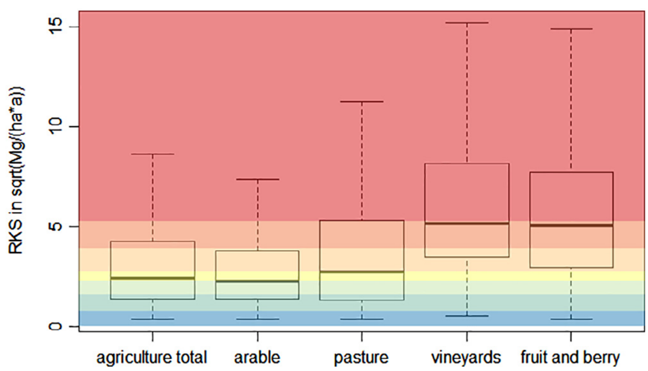

Fig. 2. Boxplots of RKS-values on agricultural land in Germany (sample of 2e + 07 raster cells). The line that divides the box into 2 parts represents the median of the sample. The ends of the box show the upper (Q3) and lower (Q1) quartiles. The difference between Q 1 and Q 3 is called the interquartile range (IQR). The whiskers show Q3 + 1.5·IQR to Q1-1.5·IQR (the highest and lowest value excluding outliers). Outliers are not drawn. To improve the clarity of the plot in the lower range of values, the square root was taken from the RKS values. The background colors represent the risk classes $E_{pot}0$ to $E_{pot}6$ according to DIN19708 (Table 1).

(sd = 76.0 Mg ha^{-1} a^{-1}).

3.2. *Model comparisons: the potential risk of soil erosion by water according to the alternative KS and RKLS classification of the German DPR*

For the erosion classification of arable land, only the consideration of the K- and S-factors is legally prescribed. Based on the RKS classification according to DIN 19708, the classification of KS-factors according to the German DPR corresponds to the assumption of an average annual precipitation of approx. 670 mm (R-factor = 50). However, according to the new R-factor map of Germany from 17 years of radar rain data by Auerswald et al. (2019), the average annual R-factor on arable land in Germany is much higher ($\bar{x}$ = 84.4, sd = 20.4). R-factors on arable land in Germany range from 45 to 359. Thus, if the R-factor is omitted and the simplifying classification based on the KS-factors is applied, the potential risk of soil erosion on German agricultural land is greatly underestimated almost across the board. Particularly in the high-precipitation *Alpine foothills*, the *Ore Mountain Foreland* and other low mountain ranges, and on the coasts of northern Germany, there is a risk that farmers will not have to take erosion control measures even though the actual soil loss may be considerable (Fig. 3). Compared to the simplified KS classification scheme according to the German DPR, about 55% of German arable land is classified in a higher risk category after inclusion of the R-factor.

Likewise, the risk classification of RKLS-values according to the German DPR refers to the assumption of a cross-regional standard slope of 100 m in length (L-factor approx. 2) (Bundesrat, 2008). Auerswald et al. (2009) even suggest using standard slope lengths of 200 m. In comparison, the evaluation of the high-resolution DGM 10 and LBM-DE land use data using the UCA algorithm according to Desmet and Govers (1996) leads to a pronounced spatial differentiation of regional L-factors: According to the modelling presented here, the national average of L-factors on agricultural land is 1.63. The UCA algorithm, on the other hand, also yields significantly longer flow paths at some sites compared to the standard slope length - exemplified in Fig. 4 (Panagos et al., 2015b; Wurbs and Steininger, 2011; Tetzlaff et al., 2013). Standard deviation of the L-factor on agricultural land is 4.44, which indicates the large regional and local variation of effective slope length on German agricultural land. Here, again, it is evident that the simplifying assumptions on the average slope length on German arable land in the German DPR lead to a considerable under- or overestimation of the local potential risk of soil erosion, respectively.

The total average of RKLS-values on agricultural land in Germany is 19.4 Mg ha^{-1} a^{-1} (sd = 64.4 Mg ha^{-1} a^{-1}). The average RKLS-value is 13.6 Mg ha^{-1} a^{-1} (sd = 30.1 Mg ha^{-1} a^{-1}) on arable land, 28.7 Mg ha^{-1} a^{-1} (sd = 99.2 Mg ha^{-1} a^{-1}) on permanent grassland, 61.3 Mg ha^{-1} a^{-1} (sd = 107.4 Mg ha^{-1} a^{-1}) on vineyards, and 49.0 Mg ha^{-1} a^{-1} (sd = 96.9 Mg ha^{-1} a^{-1}) on orchard plantations, respectively.

In summary, when applying the classification standards of the German DPR it is by no means irrelevant whether either the combined KS, RKS or RKLS factors are used to determine the potential risk of soil erosion by water. The range of values for both the R-factor and the L-factor within and between the agricultural regions of Germany is too wide to be adequately represented by standard values. This finding is illustrated in Fig. 5. If the assumptions about standard R- and L-factors in Germany were appropriate, the boxplots would have to show a similar frequency distribution. However, this is clearly not the case. The integration of the R- and L-factors is particularly important for identifying extremely erosion-prone sites and sub-sites. These areas may not represent a significant proportion of the total agricultural area, but they are of paramount relevance for cost-efficient soil and water protection management.

4. Discussion

In order to reassess the risk of soil erosion by water on agricultural land in Germany, the latest and highest resolution geo-information on soil properties, topography, land use and precipitation patterns in Germany were evaluated.

To the best of my knowledge, this is the first attempt to analyze the new *Digital 1:200.000 Soil Map of Germany* (BÜK 200) and the new R-factor map for Germany by Auerswald et al. (2019) for a nationwide modelling of soil erodibility on agricultural land in Germany. Compared to the previous version BÜK 1000 N, the introduction of BÜK 200 is suggested to be a milestone in the assessment of soil hazards in Germany (Wurbs and Steininger, 2011; Krug et al., 2013): Particularly where the aggregation rules of BÜK 1000 N obscure the small-area mosaic structures of different soils and their properties, the analysis of the BÜK 200 map set leads to a revaluation and occasionally to a

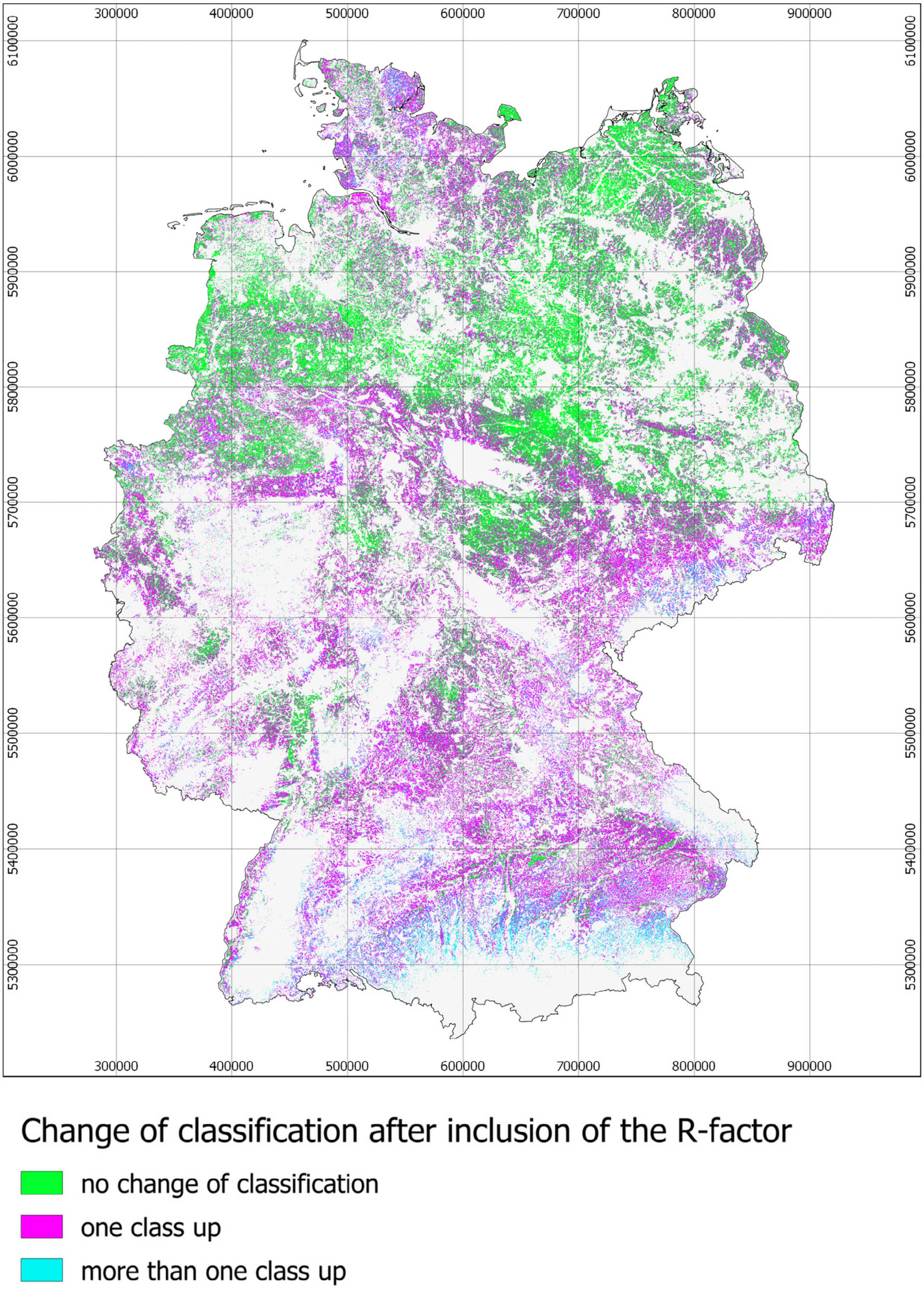

Fig. 3. Comparison of KS- and RKS-classification of the potential risk of soil erosion by water according to the German DPR. Change of classification on arable land after inclusion of the new R-factor map by Auerswald et al. (2019). Please note that a very small proportion of arable land (about 1.330 ha) is classified in a lower risk class after integration of the R-factor. These areas are not shown separately in the figure.

reclassification of the locations. At present, a considerable proportion of agricultural land in eastern and southeastern Germany is not yet covered by the BÜK 200. After completion of the relational BÜK 200 soil database, the remaining spatial gaps must be successively closed in order to round off the nationwide picture of soil erodibility on agricultural land in Germany.

For all that - in view of the often small-scale changes in soil properties and cultivation patterns on agricultural land in Germany, the BÜK

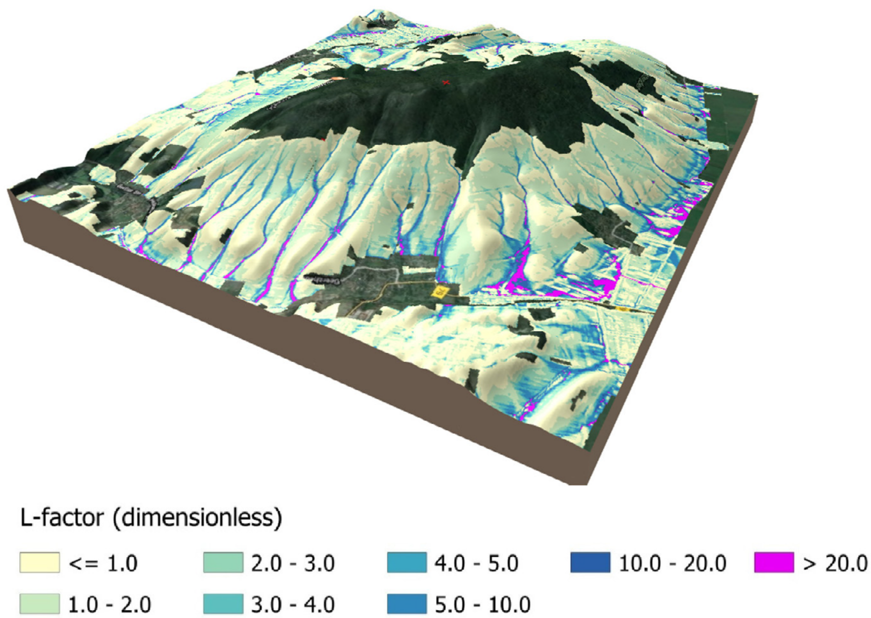

Fig. 4. Modelling of the slope length (L-factor) on arable land. The map section (approx. 60 ha) shows arable land on the foothills of *Osteroder Holz* (613885.6, 5760377.4: 622681.9, 5767098.0). The aerial photograph is taken from Google Hybrid. Vertical exaggeration factor = 5.0.

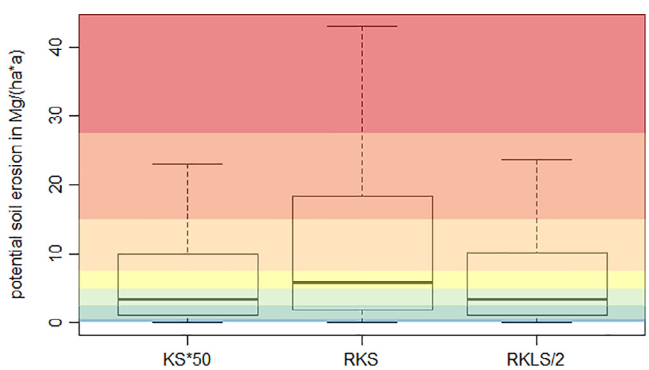

Fig. 5. Comparison of the potential risk of soil erosion by water on agricultural land, according to the classification rules of the German DPR. KS-Factors are multiplied by 50 (corresponds to a standard R-factor of 50) and RKLS-factors are divided by 2 (standard L-factor of 2).

200 soil database is an important but nevertheless intermediate step towards a site-specific modelling of soil erodibility at larger spatial scale: The BÜK 200 continues to combine individual soils into regional associations of soils and to present soil properties in content classes on an ordinal scale. The processing of soil properties that are both site-specific and specific to land use is therefore still not possible in a fully satisfactory way. In this study, I have put forward a tentative proposal on how the soil properties of minor associated soils within regional associations of soils can be taken into account.

The fact that only surrogate data is available for deriving the K-factors on a national scale is very regrettable and difficult to accept, as high-resolution geo-information on relevant soil parameters is available at the federal state level, but kept under lock and key. In this context, a very promising alternative to BÜK and higher resolution BK data is the so-called *Bodenschätzung*. The original purpose of this data set is to provide a uniform evaluation bases for the taxation of agricultural land in Germany on the basis of its specific productive potential (BMJV, 2007). The *Bodenschätzung* focuses on the characteristics of the topsoil A-horizons, which are particularly relevant both for the assessment of the soils' agricultural yield potential and for its susceptibility to soil erosion by water (Auerswald, 1987). This is a decisive advantage over pedogenetic BÜK and BK maps, which mainly use characteristics of the subsoil B-horizons to differentiate between soil associations. Unfortunately, the data records of the *Bodenschätzung*, which are maintained by the fiscal authorities of the German federal states, are currently not freely available and not uniformly georeferenced. However, it should be worthwhile to acquire and bundle the federal states' *Bodenschätzung* data for a nationwide reassessment of K-factors on agricultural land. In close cooperation with the responsible federal state authorities, perspectives for the joint evaluation of the proprietary data should be discussed.

The availability of increasingly better digital elevation models improves the accuracy of the L- and S-factor predictions. In large-scale erosion modelling, grid-based flow-routing algorithms are increasingly accepted to compute the L-factor (Zhang et al., 2017; Garcia Rodriguez and Gimenez Suarez, 2012; Hickey, 2000; Winchell et al., 2008). As proposed by Panagos et al. (2015b), in this study the L-factor was calculated in great detail using the high-resolution DGM 10 elevation data, latest and high-resolution LBM-DE land use data, a flow-routing UCA algorithm according to Desmet and Govers (1996), and High Performance Computing resources of GWDG. Surface depressions were identified and filled according to Wang and Liu (2006). This approach is considered a significant improvement on past erosion risk assessments for Germany that used either 50 m DEMs (Wurbs and Steininger, 2011) or cross-regional standard estimates of slope length (Auerswald et al., 2009; Saggau et al., 2017). There is strong modelling evidence that the assumption of cross-regional standard upslope lengths leads to over- and underestimations of local L-factors and hence systematic misjudgments about the local risk of soil erosion on agricultural land in Germany. As a consequence, farmers will be subject to farming restrictions whose costs may be disproportionate to their environmental performance. The main limitation of the applied methodology is the disregard of smaller landscape and infrastructure features, which actually reduce the length of slopes, but are not identified neither in DGM 10 nor in LBM-DE (Panagos et al., 2015b). The specific retention capacity of different linear runoff barriers cannot be considered on the basis of the available geodata either. Ongoing research on the identification of small-scale landscape structures (Graham et al., 2019) and the delimitation of individual agricultural fields and cultivation patterns by means of remote sensing (Bégué et al., 2018; Griffiths et al., 2019) is promising for the improvement of L-factor approximations. The average slope length derived from the digital terrain model in this study is remarkably short, but is within the range calculated for arable land and permanent grassland in Germany by Panagos et al. (2015b). The low estimate may be due to both the UCA method used, the DEM input data and the preprocessing of the terrain model. Hrabalíková and Janeček (2017) examined five GIS-based approaches (including the Desmet and Govers, 1996 algorithm) and two manual procedures to compute LS-factors, and then compared modeled and measured soil loss rates. The results indicate that the LS-values generated by the GIS-methods are generally lower than those obtained by the manual methods and underpredict mean annual erosion. The relative performance of the GIS-based flow-routing algorithms depends largely on the resolution of the digital terrain models (Hrabalíková and Janeček, 2017; Yitayew et al., 1999). It can be assumed that a smoothing of the terrain model, which is common when using DEMs with lower resolution, would lead to higher modelling results of the L-factor, especially in low-relief areas. Against the background of the large number of available flow-routing algorithms and specifications in the international research literature, the slope lengths modelled in this study have to undergo field-based validation and - if necessary - further adjustment (Boardman, 2006; Hrabalíková and Janeček, 2017; Wilson et al., 2007).

The new R-factor map derived from a 17-year record of radar rain data by Auerswald et al. (2019) is of the utmost importance for a comprehensive assessment of the risk of soil erosion by water in Germany. Their approach enables a supra-regional analysis of the influence of precipitation intensity and quantity on soil erosion on a uniform methodological basis and avoids the inaccuracies of the regression equations which have been used previously. The particular attraction of this work is that the influence of climate change can be illustrated in a continuous analysis of precipitation patterns and can be used to update erosion modelling. According to Elhaus et al. (2019), the R-factor in Germany is increasing at a rate of 10% in six years due to an increase in extreme precipitation events. Against this background, they propose using the mean R-factor of a pivotal year 2025 in order to ensure the comparability and planning reliability of any future risk assessment of soil erosion. Corresponding guidelines should be included in the forthcoming new edition of the DIN standard 19708.

Both soil protection policy and soil erosion modelling have so far focused on arable land: Under real farming conditions, soil erosion takes place mainly on arable land (Auerswald et al., 2009). Perennial meadows and pastures are protected from significant soil loss by permanent vegetation cover. Although of great regional importance, the area under vineyards and orchards in Germany is small. Locally, the soil loss here is considerable, but it is hardly significant on a national scale. However, the present assessment of soil erosion risk shows that many permanent meadows and pastures cover soils, which are most susceptible to erosion by water in the absence of permanent vegetation cover. Against that background, preservation and maintenance of the extensive grasslands at low mountain range is of utmost importance for soil and water conservation in Germany – and should be actively supported by soil protection policy. Today, some 28% of Germany's agricultural land is permanent grassland (Destatis, 2020a,b). Between 2003 and 2012, the proportion of grassland decreased by around 5% (Nitsch et al., 2012; BfN, 2008; BfN, 2013). Since 2013, when the maintaining of permanent grassland was introduced as one of the three greening obligations under the 2013 CAP reform, the area and proportion of permanent grassland in Germany remained stable (Destatis, 2020b). Within the framework of the *greening* of the CAP, environmentally sensitive permanent grassland has special protection: For permanent grassland defined as environmentally sensitive, a complete ban on conversion and ploughing applies. Permanent grassland on soils with a high potential risk of erosion, however, has so far not been classified as environmentally sensitive. The protection of ecologically valuable grassland - and this necessarily includes grassland on erosion-prone sites - is a high priority in view of the forthcoming reform of the CAP. However, a ban on the conversion of grassland into arable land cannot provide a permanent solution to the loss of grassland. Rather, the agricultural policy challenge is to create stable framework conditions for competitive grassland management.

Among the cultivated lands in Germany, vineyards and orchard plantations also deserve special attention. In contrast to permanent grassland, vineyards and orchards are expected to undergo massive soil erosion under real farming conditions. According to Rodrigo-Comino (2018), the phenomenon of soil erosion in vineyards is at best a scientific issue, but not an important agronomic or ecological concern. The presented modelling of the natural risk of soil erosion clearly shows that effective erosion control measures both in wine- and fruit-growing can make a substantial contribution to improving regional surface water quality.

In summary, the forthcoming new edition of the DIN standard 19708 should be taken as an opportunity to completely redesign the assessment and classification of the potential risk of soil erosion by water. In the currently valid version of the standard, the combined RKS factor describes the "natural sensitivity" of a site to soil erosion by water. However, the term *sensitivity* is not further explained and specified. The only criterion for the delimitation of risk levels is the expected gross soil loss on a given area (Table 1). However, in order to be able to make an informed decision on the necessity of preventive erosion control measures, it is of decisive importance on which soil and in which ecological environment soil erosion takes place. With regard to both the on-site and the off-site sensitivity of agricultural land to soil erosion, a simple reference to gross soil loss is insufficient. To assess the on-site sensitivity of agricultural land, the depth of the affected soil and the loss of soil fertility associated with each unit of soil erosion must be determined in order to establish tolerance thresholds for soil loss (Auerswald, 1987). Furthermore, a fully comprehensive assessment of the off-site risk potential of soil erosion on agricultural land requires the analysis of both land use and cropping patterns (C- and P-factors of the (R)USLE/ABAG) as well as a modelling of sediment delivery into connected surface waters (van Rompaey et al., 2001; Tetzlaff et al., 2013; Borrelli et al., 2018). Last but not least, there is great demand for research on the mapping of the local sensitivity of downstream ecosystems (i.e. critical loads) to diffuse nutrient and pollutant inputs (UBA, 2018). The challenge for large-scale erosion modelling is to validate the results using manually collected data and to identify artefacts, which result from inaccuracies and inconsistencies of the heterogenous input data.

5. Conclusion

We can only preserve ecosystem functions if we stop the continuing degradation and destruction of natural resources and place at-risk areas under special protection. Due to the heterogeneity of topography, landscape, soil, and precipitation patterns in Germany, the risk of soil erosion by water varies greatly from one agricultural region to another. Site and land use specific soil erosion control measures are therefore required. At present, federal state authorities have a great deal of flexibility in the designation of soil erosion protection areas under the German DPR: First, the assessment both of rainfall erosivity (R-factor) and slope length (L-factor) is only optional. However, in view of the great diversity of agricultural structures and natural site conditions, it is inappropriate to determine the risk of soil erosion on the basis of either the KS-, RKS- or RKLS-factors. Second, classifications of KS- and RKLS-factors according to the German DPR correspond to the assumption of cross-regional standard estimates for precipitation and slope length. The present study shows that these assumptions do not adequately reflect local site conditions. There is a great danger that economically inefficient, competition-distorting and ecologically ineffective management requirements will be imposed on German farmers on the basis of existing classification instructions. Therefore, the legal guidelines for classifying the potential risk of soil erosion on agricultural land and the assessment of the on-site and off-site sensitivity to soil erosion should be fundamentally revised. Free access to high-resolution environmental and land use data and the exchange of information between research institutions and public authorities are crucial for improved decision-making in soil and water protection.

CRediT authorship contribution statement

Nils Ole Plambeck: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106732.

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