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Monthly RUSLE soil erosion risk of Swiss grasslands

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ABSTRACT

This study presents the first mapping of soil erosion risk modelling based on the Revised Universal Soil Loss Equation (RUSLE) at a sub-annual (monthly) temporal resolution and national scale (100 m spatial resolution). The monthly maps show highest water erosion rates on Swiss grasslands in August (1.25 t ha^{-1} $month^{-1}$). In summer, the mean monthly soil loss by water erosion is 48 times higher than the mean soil loss in winter. Considering the annual average fraction of green vegetation cover of 54%, the predicted soil erosion rate for the Swiss national grassland area would add up to a total eroded soil mass of 5.26 Mt yr^{-1}. The RUSLE application with an intact 100% vegetation cover would largely reduce the soil loss to an average annual rate of 0.14 t ha^{-1} $year^{-1}$. These findings clearly highlight the importance to consider and maintain the current status of the vegetation cover for soil erosion prediction and soil conservation, respectively.

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KEYWORDS
Soil loss; modelling; revised universal soil loss equation; Switzerland

1. Introduction

Soil erosion is a serious threat to soils worldwide. Currently, 6.1% of the global land surface is affected by severe soil erosion that exceeds a global tolerable soil loss threshold of 10 t ha^{-1} yr^{-1} (Borrelli et al., 2017). The annual global soil loss by water is estimated to be 35.9 billion tons for the year 2012 (Borrelli et al., 2017). The cost induced by soil erosion for the European Union is about 1.25 billion Euros per year (Panagos et al., 2018). Soil erosion control could not only reduce these costs for agriculture but could also protect the valuable soil resource (Kuhlman, Reinhard, & Gaaff, 2010; Panagos et al., 2016). Some protection measures (e.g. fencing of risk zones) could be even more efficient if they were implemented by spatial and temporal targeting of specific areas during the riskiest seasons of a year (Troxler, Chatelain, & Schwery, 2004). So far, soil erosion by water in Switzerland is modelled on an annual basis despite known temporal variations of soil loss (Prasuhn et al., 2013) and rainfall erosivity(Meusburger, Steel, Panagos, Montanarella, & Alewell, 2012; Schmidt, Alewell, Panagos, & Meusburger, 2016). Simultaneous identification of both, risky areas and risky seasons is urgently needed. Recently, Borrelli et al. (2018) stated that the lateral carbon transfer from erosion in noncroplands on a global scale 'may play a more important role than previously assumed' because too little is known about erosion on grasslands and their impact on erosion rates is thus usually underestimated. The same knowledge gap also exists for Switzerland. However, soil loss has been observed and measured in many small scale studies by different techniques (e.g. by rainfall simulation experiments, plot experiments, tracing techniques, modelling; Alewell, Meusburger, Juretzko, Mabit, & Ketterer, 2014; Konz, Prasuhn, & Alewell, 2012; Martin, Pohl, Alewell, Körner, & Rixen, 2010; Meusburger, Konz, Schaub, & Alewell, 2010b; Schindler Wildhaber, Bänninger, Burri, & Alewell, 2012) and was identified to be severe at disturbed hotspots (>3 t ha^{-1} yr^{-1}; Alewell, Egli, & Meusburger, 2015; Meusburger et al., 2010b). Since grassland areas are the dominant agricultural land use unit in Switzerland (Hotz & Weibel, 2005) they should be included in Swiss soil erosion risk maps. The common assumption of nearly zero soil loss on grasslands by the protective characteristics of the closed vegetation cover should be reconsidered, as about 6.5% of the land surface is covered by grassland (based on global CCI Land Cover 2015 data; Arino & Ramoino, 2017) with a high percentage of the grassland having low and/or damaged vegetation cover (Gallo et al., 2001; Meusburger, Bänninger, & Alewell, 2010a).

With the recent development of geoinformation tools and the improved quality and availability of geodata, a national assessment of the soil erosion risk for Swiss grassland is now feasible.

One of the most commonly used erosion models for modelling soil loss is the Universal Soil Loss Equation (USLE; Wischmeier & Smith, 1978) and its revised version (RUSLE; Renard, Foster, Weesies, & Porter, 1991). These empirical models are based on a multiplication

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of single erosion risk factors (rainfall erosivity R, soil erodibility K, cover and management C, slope length and steepness LS, support practices P).

A high intra-annual variability can generally be expected for R and C, as these factors are related mainly to the natural temporal variability of precipitation and plant growth (Renard, Foster, Weesies, McCool, & Yoder, 1997). the temporal variation of the K-factor is discussed by Kinnell (2010). However, temporal changes of the K-factor are rather expected for a multi-annual scale (Wang, Gertner, Liu, & Anderson, 2001). The factors LS and P are relatively static as long as no natural (e.g. landslides) or human-induced changes (e.g. implementation of new protection measures) occur (Panagos, Karydas, Gitas, & Montanarella, 2012). Thus, modelling of the variable R and C factors at a sub-annual scale is essential to increase the explanatory power of soil erosion prediction. Wischmeier and Smith (1965) propose a monthly temporal resolution to be appropriate for soil erosion modelling. This recommendation was affirmed four decades later by Panagos et al. (2016) and Karydas and Panagos (2016). Quantifying soil loss on a seasonal, monthly, weekly or even daily time-scale helps to improve our mechanistic understanding and allows for targeted protection measures. The recent availability of high temporal resolution spatial datasets (Alexandridis, Sotiropoulou, Bilas, Karapetsas, & Silleos, 2015) enables a high temporal resolution of rainfall erosivity and of the cover and management factor. Several studies across the world use at least daily rainfall records to calculate the R-factor (e.g. Angulo-Martínez & Beguería, 2009; Ma, He, Xu, van Noordwijk, & Lu, 2014) and model the R-factor on a seasonal (Nunes, Lourenço, Vieira, & Bento-Gonçalves, 2016) or monthly scale (Ballabio et al., 2017). The modelling of monthly C-factors is presented by Yang (2014) for New South Wales, Australia with a spatial resolution of 500 m and Alexandridis et al. (2015) for Northern Greece aggregated on a catchment scale. Soil loss by water was modelled with monthly resolution by Evrard, Persoons, Vandaele, and van Wesemael (2007) and Inoubli, Raclot, Mekki, Moussa, and Le Bissonnais (2017) for selected catchments in Belgium and Tunisia. However, so far spatiotemporal large-scale soil erosion maps are relatively rare. National monthly soil erosion maps can only be found for Albania (Grazhdani & Shumka, 2007) and Mauritius (Nigel & Rughooputh, 2010).

The objective of the present study is to (i) quantify the monthly rates of soil loss of Swiss grasslands and (ii) delineate the spatial and temporal patterns of soil erosion risk.

2. Material and methods

2.1. Study area

Switzerland has high climatic contrasts owing to variations in topography (from 192 m a.s.l. to 4633 m a.s.l.) (Figure 1). The long-term (1981–2010) mean precipitation in Switzerland (measured at 418 stations; MeteoSwiss, 2018b) is 1299 mm following the humid continental to oceanic climate zone with highest rainfall in summer and lowest in winter. The typical melt-out date for alpine elevation ranges is in the late spring (DOY 147, 27th of May) (Jonas, Rixen, Sturm, & Stoeckli, 2008). This late melt-out in the Alps shortens the plant growth period in higher elevations. Soils of Switzerland are dominated by Cambisols (King, Daroussin, & Tavernier, 1994). Switzerland can be subdivided into five main geological units: the Alps mainly dominated by granite, the Jurassic, a young fold mountains of limestone, the partly flat, partly hilly Swiss Midland (between Jura and Alps) and of minor spatial extend are the Po Valley at the southernmost tip of Ticino (Southern Alps), and the Upper Rhine Plain around Basel.

Mapping of the seasonality of soil erosion by water was undertaken for the national grassland area of Switzerland, which covers to about 28% (11.559.800 ha) of the Swiss national territory and accounts for 72% of the total agricultural area (Bötsch, 2004; Jeangros & Thomet, 2004). Grassland areas are distributed widely with a major extent in the Alps (Hotz & Weibel, 2005). They are usually used as pastures or hayfields for fodder production. Alpine grasslands are commonly covered by snow in winter. Permanent grassland areas, which are not being part of the crop rotation for a minimum of five successive years, have slowly but steadily increased over the last two decades in Switzerland (Schmidt, Alewell, & Meusburger, 2018a).

2.2. Datasets

To depict the grassland extent of Switzerland, the grassland class in the global Climate Change Imitative (CCI) Land Cover dataset was used and refined with topographic models of Switzerland (Schmidt et al., 2018a). That grassland map serves as the mask for modelling soil erosion by water on Swiss grasslands.

Each of the RUSLE-factors (excluding the P factor) was calculated separately and adapted to the specific environmental conditions of Swiss grasslands. The generation of the RUSLE factor maps (rainfall erosivity, Schmidt et al., 2016; soil erodibility, Schmidt, Ballabio, Alewell, Panagos, & Meusburger, 2018c; cover and management, Schmidt, Alewell, & Meusburger, 2018b; slope length and steepness, Schmidt, Tresch, & Meusburger, 2019) is explained in detail in the individual sections and in Table 1.

The high-resolution spatial datasets of the Swiss Federal Offices (e.g. SwissAlti3D Digital Elevation Model 2 m spatial resolution, SwissImage Orthophoto 0.25 m spatial resolution) are among the most detailed in Europe. They allow modelling of the spatiotemporal patterns of soil erosion for Swiss grassland in combination with temporal datasets (e.g. Rainfall

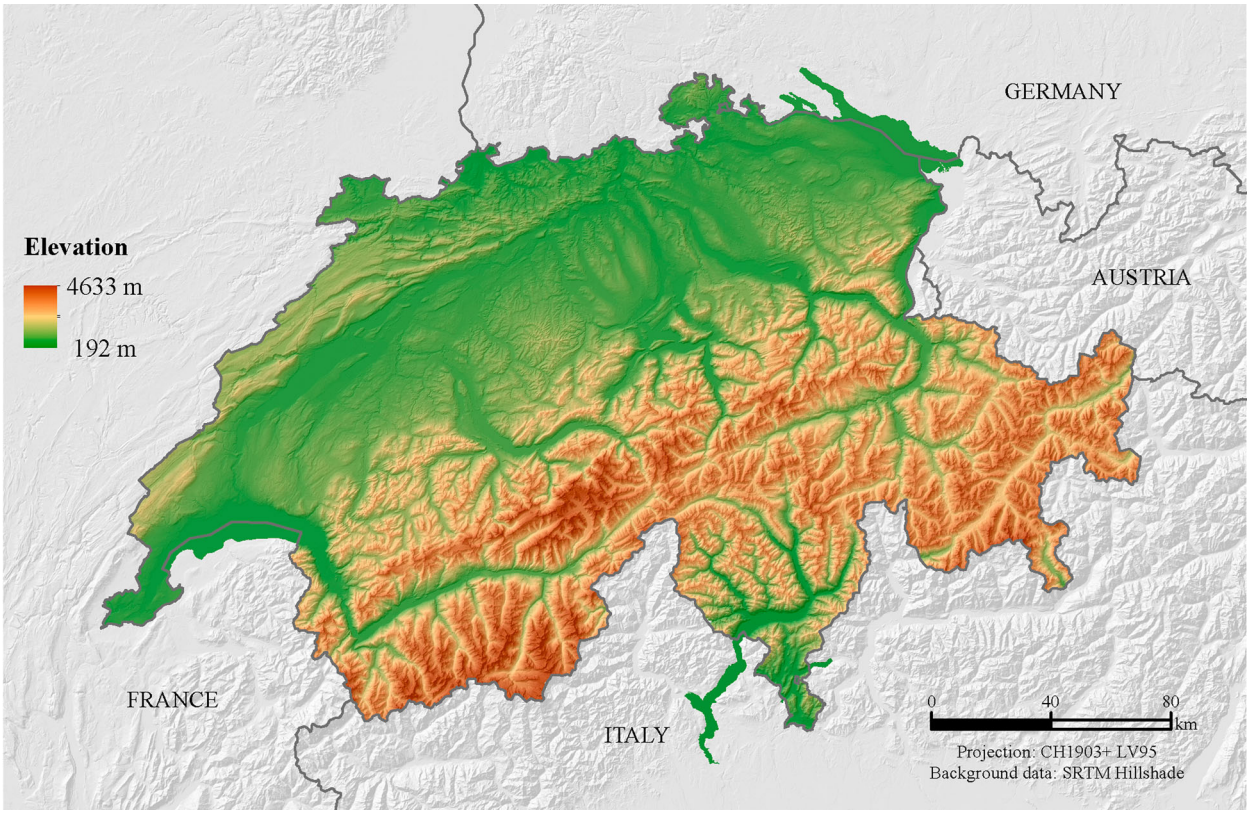

Figure 1. Topography of Switzerland including the Swiss Alps (data source: SwissAlti3D, 2 m spatial resolution).

measurement 10 min temporal resolution, Copernicus FCover 10 day temporal resolution).

2.3. Mapping

All (R)USLE-factors are multiplied according to the following equation by Wischmeier and Smith (1965) and Renard et al. (1997):

$$A = R*K*C*L*S*P \quad (1)$$

where A is usually the soil loss in t ha^{-1} yr^{-1}. The equation can be modified to a monthly soil erosion equation by including a monthly temporal resolution of the dynamic factors R and C (Schmidt et al., 2016, 2018b):

$$A_{month} = R_{month}*K*C_{month}*L*S*P \quad (2)$$

where A_{month} is the quantification of soil loss in t ha^{-1} $month^{-1}$.

The R-factor was regionalized on a monthly scale by regression-kriging with 87 automated gauging stations, serving as dependent variable and high resolution spatial and temporal covariates, serving as independent variables (Table 1). Dynamics in the cover and management factor for Swiss grasslands were assessed by a linear spectral unmixing of high spatial resolution orthophotos and normalized by temporal variations of the fraction of green vegetation cover. The potential soil loss of a specific plant development stage expressed as soil loss ratio (SLR), was then weighted by the rainfall erosivity ratio to generate in monthly C-factor maps (Table 2).

Soil erodibility on a national scale is a result of a cubist regression and multilevel B-splines of a total of 1837 Land Use/Cover Area Survey (LUCAS) topsoil samples (Orgiazzi, Ballabio, Panagos, Jones, & Fernández-Ugalde, 2018) and independent variables (Table 1). Finally, the L and S factors were adapted to the complex alpine topography (Table 2). Slope length were originally constrained to a maximal flow threshold of 100 m to account for the whole agricultural area in Switzerland (Schmidt et al., 2019). However, flow measurements in the Swiss alpine grasslands revealed short flow length less than 2 m due to high surface roughness and infiltration capacity. These observations lead to the assumption that the influence of the L-factor is minimal. In future, more empirical data is needed to support this assumption. Therefore, an L-factor of 1 is used for predicting the soil loss of Swiss grasslands to comply with field observations. Slope steepness was predicted by a mean equation (S_{alpine}) of a total of 12 empirical S-factor equations. The regionalization of the support practice factor was difficult to obtain for Swiss grasslands because of a lack of spatial information on grazing management and its effect on soil loss. Thus, the P-factor was set to 1 (not influential) for this study, even though the authors are aware of the substantial variation of management and its effect on soil loss (e.g. stocking numbers and rotation frequency of lifestock as well as watering places, fencing, and herding).

Table 1. Overview of RUSLE factor maps used for the soil erosion risk mapping of Swiss grasslands.

Erosion factor	Dataset	Derived variable	Data source
Rainfall erosivity R	Rainfall station data	Long-term rainfall measurements at 87 stations	MeteoSwiss, 2018a
	Snow depth	Monthly snow depth	MeteoSwiss, 2018a
	CombiPrecip	Rainfall amount (measured and radar)	Sideris, Gabella, & Germann, 2014
	EURO4M-APGD	Daily precipitation per month	Isotta et al., 2014
	RhiresM	Monthly precipitation sums	MeteoSwiss, 2013
	SwissAlti3D	Elevation, slope, aspect	Swisstopo, 2018
Soil erodibility K	LUCAS topsoil	199 Swiss and 1638 European topsoil samples	Orgiazzi et al., 2018
	MODIS13Q1	NDVI, Enhanced Vegetation Index EVI, Raw bands	Didan, Munoz, Solano, & Huete, 2015
	EU-DEM	Elevation, slope, base level of streams, altitude above channel base level, multi-resolution index of valley bottom flatness	Farr et al., 2007
	Location parameter	Latitude, longitude	–
Cover and management C	Swissimage FCIR	Spatial distribution of the fraction of green vegetation cover	Swisstopo, 2010
	FCover300m	Temporal distribution of the fraction of green vegetation cover	Smets et al., 2017
	MOD13Q1	NDVI	Didan et al., 2015
	CCI land cover	Dynamic long-term snow occurrence	Arino & Ramoino, 2017
Slope length L	SwissAlti3D	Upslope contributing area	Swisstopo, 2018
Slope steepness S	SwissAlti3D	Slope	Swisstopo, 2018

Table 2. Erosion factors for the monthly soil erosion modelling of Swiss grassland.

Erosion factor	Method description	Spatial resolution	Temporal resolution	Factor source
Rainfall erosivity R	Regression-kriging	100 m	Monthly	Schmidt et al., 2016
Soil erodibility K	Cubist regression	500 m	–	Schmidt et al., 2018c
Cover and management C	Linear spectral unmixing	100 m	Monthly	Schmidt et al., 2018b
Slope length L	Upslope contributing area with Maximal flow threshold	2 m	–	Schmidt et al., 2019
Slope steepness S	Modification of S-factor for alpine environments (S_{alpine})	2 m	–	Schmidt et al., 2019

The multiplication of all RUSLE factors (according to Eq. 2) provides monthly soil erosion risk maps for Swiss grasslands (Figure 2). Note that while the K-factor (Schmidt et al., 2018c), R-factor (Schmidt et al., 2016), and LS-factor (Schmidt et al., 2019) are available for the whole of Switzerland, the C-factor (Schmidt et al., 2018b) is limited to the grassland areas of Switzerland (Schmidt et al., 2018a) and thus presets the extent of the erosion modelling.

The maps were visually interpreted regarding their spatial and temporal patterns of soil erosion risk. In addition, descriptive statistics for all twelve monthly erosion maps were calculated.

The maps were evaluated by a sensitivity analysis of the dynamic and annual soil loss rates. Such a sensitivity analysis contrasts the differences between dynamic and static erosion factors. For the non-dynamic assessment, the mean monthly R- and C-factor maps over a year were multiplied with the annual factors K, LS and P.

3. Results and discussion

3.1. Monthly soil erosion rates for Swiss grasslands

Spatially, the grasslands in the Alps are more prone to soil erosion in most of the months than those in the Swiss lowlands, owing to the influence of topography on the RUSLE model (please note that due to regional snow cover, the predicted area is considerably reduced in winter). Given an intact 100% vegetation cover the annual sum of soil loss as cumulative sum of monthly soil losses is 0.14 t ha^{-1} yr^{-1}. However, considering the actual fraction of green vegetation cover (average annual FGVC = 54% mapped for the period 2014–2016 based on FCover300m; Smets, Jacobs, & Verger, 2017) the annual sum of soil loss as cumulative sum of the monthly soil losses rises up to 4.55 t ha^{-1} yr^{-1}. The latter is significant, as the mean annual value for Europe including arable lands was calculated as 2.5 t ha^{-1} yr^{-1} (Panagos et al., 2015), and exemplifies the potential vulnerability of Swiss grassland soils to soil erosion if the vegetation cover is disturbed or removed. Moreover, this clearly highlights the sensitivity of RUSLE based models to the status of vegetation cover, that should be more carefully observed in future studies.

The calculation of soil loss risk by water erosion at monthly temporal resolution allows the identification of summer as the main erosive season of Swiss grasslands. The combined effect of R- and C-factor (Meusburger et al., 2012; Schmidt et al., 2016; 2018b) is amplifying the erosion risk in summer. For Swiss grassland, July and August have the highest monthly risk of soil erosion by water (1.25 t ha^{-1} $month^{-1}$, Table 3, Figure 3). In contrast, for all winter months, a relatively low soil erosion by water risk (winter average 0.02 t ha^{-1} $month^{-1}$) was predicted (Table 3, Figure 3, Main Map) because of low rainfall erosivity (due to snow fall/ snow cover). However, processes like snow gliding and avalanches or even snow melt are not included in the present model and need to be considered separately (Ceaglio, Meusburger, Freppaz, Zanini, & Alewell, 2012; Meusburger et al., 2014; Stanchi et al., 2014). The mean monthly soil loss due to water erosion for summer is 48 times higher than the mean soil loss in winter, 6 times higher than in spring

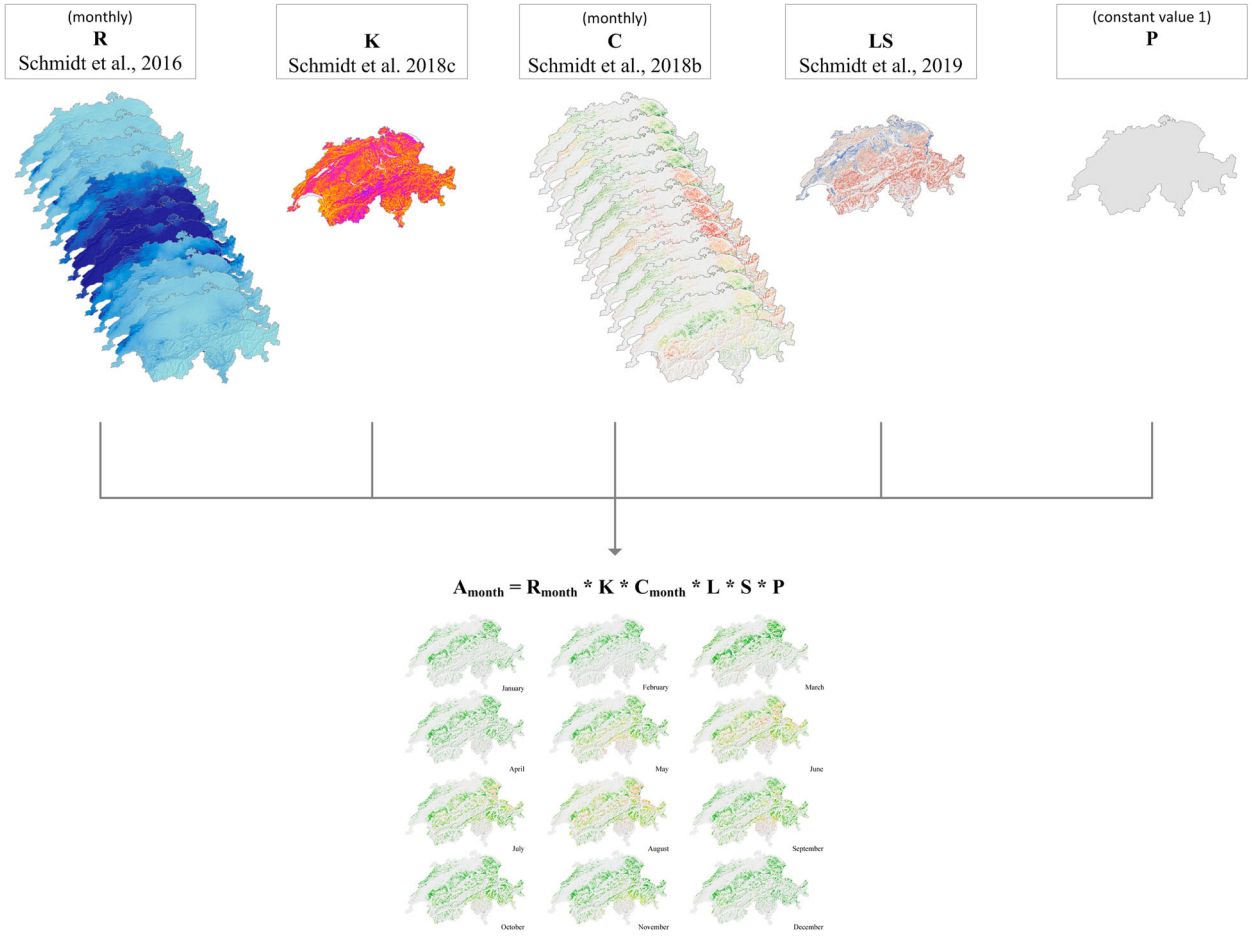

Figure 2. Flowchart of the monthly erosion maps of Swiss grassland using the RUSLE erosion factors.

and 3 times higher than in autumn (see Schmidt et al., 2018b).

3.2. Comparison of dynamic and annual soil loss rates

The benefits of a higher temporal resolution are obvious when estimated soil loss rates on a monthly temporal resolution are compared with soil loss rates on an annual resolution. The mean annual soil loss rate (4.55 t ha^{-1} yr^{-1}) would indicate hypothetical average monthly soil loss rates of 0.38 t ha^{-1} yr^{-1} (Figure 4) which would be an overestimation of mean monthly soil loss in winter (by 0.18 t ha^{-1} $month^{-1}$) and an underestimation in summer (by 0.64 t ha^{-1} $month^{-1}$). Thus a higher temporal resolution results in better knowledge of risky time periods of soil erosion by water, with a significant peak of soil loss rates on Swiss grasslands in summer and nearly zero risk of soil erosion by water in winter.

Overall, focusing on the monthly distribution of soil loss rates and rainfall erosivity (Figure 5), the latter seems to be the most influential factor regarding the intra-annual dynamics of soil loss due to water erosion(Schmidt et al., 2016). However, the rainfall erosivity is considered in the model twice, as an individual factor (Schmidt et al., 2016) and as a weighting factor for the C-factor (Schmidt et al., 2018b). Furthermore, our simulation does not consider soil loss induced by snow related erosional processes. As measurements with sediment traps or radionuclides have demonstrated, overall sediment loss is most likely highest in late winter and spring (Ceaglio et al., 2012; Meusburger et al., 2014), when avalanches, snow melt and snow ablation are triggering soil erosion on damaged and vulnerable soil surfaces.

Table 3. Monthly (t ha^{-1} $month^{-1}$) and annual (t ha^{-1} yr^{-1}) soil erosion risk averaged for the Swiss grassland area with a constraint of the maximal flow length to <1 m according to observations (L-factor equals 1). Minimum soil erosion rate is 0 t ha^{-1} $month^{-1}$ (no soil erosion) in all month.

Month	Mean soil erosion risk (t ha^{-1} $month^{-1}$)	Maximum soil erosion risk (t ha^{-1} $month^{-1}$)	Standard deviation (t ha^{-1} $month^{-1}$)
January	0.01	0.43	0.02
February	0.01	2.40	0.05
March	0.02	4.19	0.06
April	0.02	6.23	0.10
May	0.47	35.17	1.24
June	0.56	103.03	2.11
July	1.25	128.85	3.73
August	1.25	218.75	3.84
September	0.61	662.91	5.86
October	0.15	170.84	1.14
November	0.17	17.84	0.47
December	0.04	5.00	0.11
Ø	0.38	112.97	1.56
Σ (t ha^{-1} yr^{-1})	4.55	1355.62	18.71

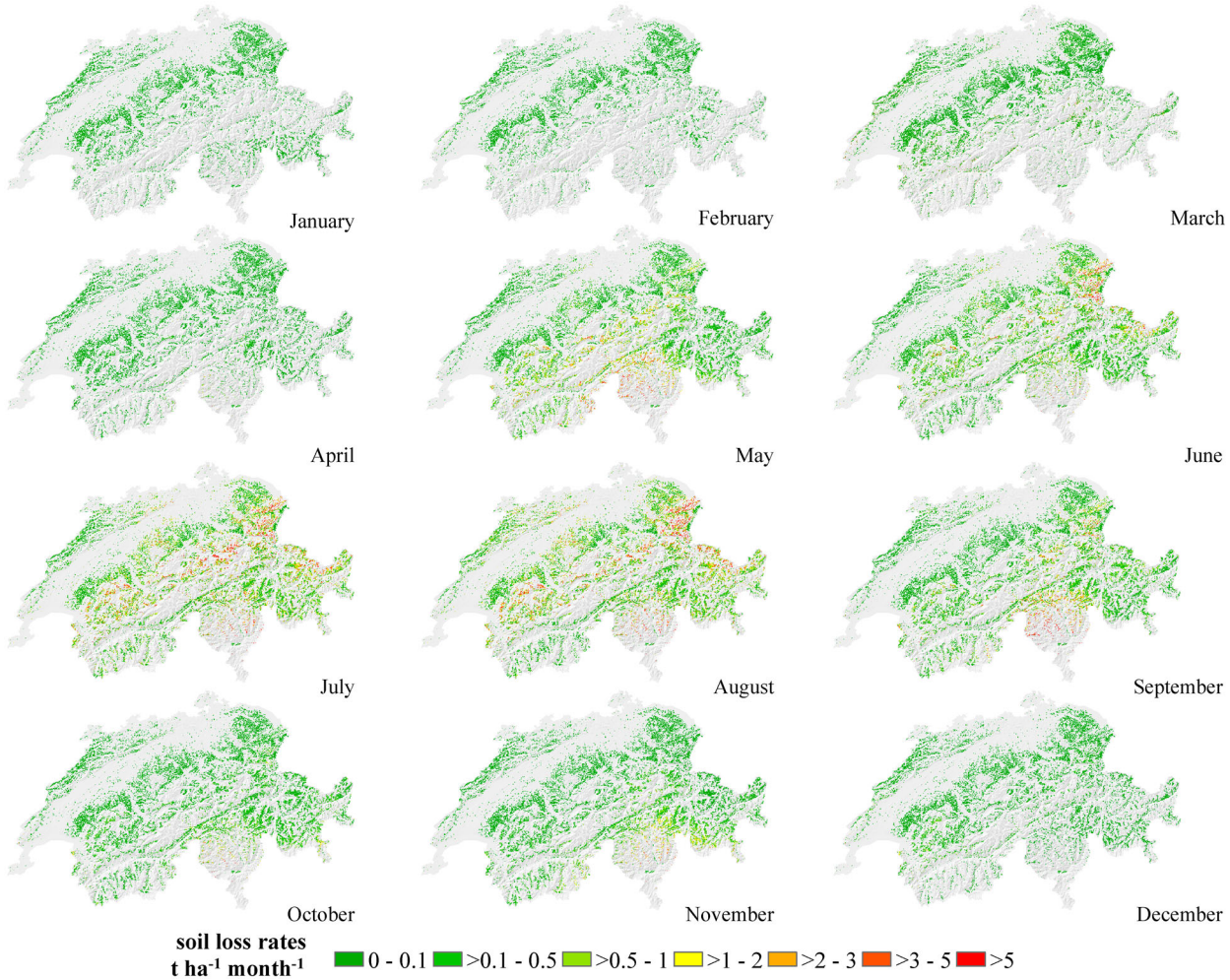

Figure 3. Spatiotemporal patterns of monthly soil erosion risk at Swiss grassland. Due to data gaps caused by snow fall in winter, the predicted area is reduced in winter. The individual maps are displayed as a multiple mapset in the supplement material.

3.3. Soil loss rates and soil formation rates

The average annual soil loss of 4.55 t ha^{-1} yr^{-1} clearly exceeds the maximum tolerable soil loss of Switzerland (2 t ha^{-1} yr^{-1}; Schaub & Prasuhn, 1998) by a factor of 2. The average annual soil erosion rate of 4.55 t ha^{-1} yr^{-1} would hypothetically equal a total eroded soil mass of 5.26 Mt per year, related to the national grassland area of 1.155.980 ha.

Soil formation rates for alpine grasslands soils with siliceous lithology were estimated by Alewell et al. (2015) as 0.54–1.13 t ha^{-1} yr^{-1} for old soils (>10–18 kyr) and 1.19–2.48 t ha^{-1} yr^{-1} for young soils (>1–10 kyr). In both cases the predicted average soil loss exceeds these rates. Only soil formation rates of very young soils (≤1 kyr; 4.15–8.81 t ha^{-1} yr^{-1}) can compensate the annual soil loss. In conclusion, the

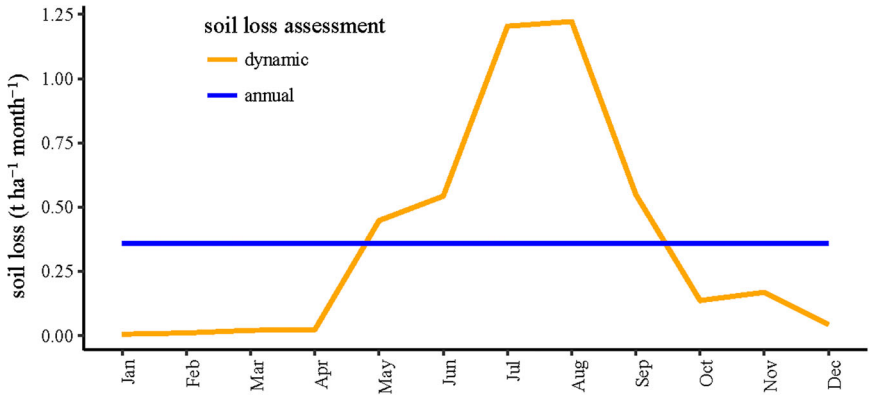

Figure 4. Comparison of the distribution of monthly soil loss rates for Swiss grasslands (dynamic) and a mean annual soil loss rate (annual), divided by twelve to result in a pseudo-monthly resolution.

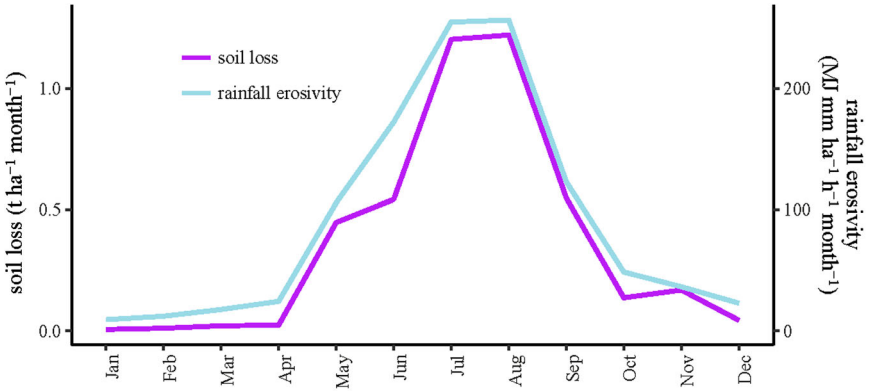

Figure 5. Influence of the temporal pattern of the monthly rainfall erosivity for the temporal pattern of the soil loss rates on Swiss grasslands.

predicted soil loss rates for Swiss grasslands imply a non-reversible loss of the valuable soil resource.

4. Conclusions

The monthly soil erosion maps presented here form the first dynamic soil erosion approach on a national scale with a monthly temporal resolution. They enable the quantification of soil erosion risk, and provide information about the spatiotemporal patterns of soil loss due to water erosion on Swiss grasslands. These patterns show that summer is the season with highest soil erosion by water risk, which is 3/6/48 times higher than in autumn/spring/winter, respectively, leaving the soil surface damaged and vulnerable for potential snow and frost induced processes (snow gliding, ablation, melt, avalanches). In contrast, to a monthly temporal resolution, annual assessments tend to overestimate the soil erosion by water risk in winter and underestimate it in summer. The analysis and integration of each erosion factor reveals that the cover and management factors is highly sensitive and that the actual state of vegetation cover is crucial. Nonetheless, regarding the intra-annual pattern the higher fraction of green vegetation cover in summer is incapable to compensate the impact of high rainfall erosivity in summer. However, the strong impact of rainfall erosivity within RUSLE, especially as a weighting factor for soil loss ratios, needs to be discussed in future studies.

The maps are suitable to quantify the actual soil erosion risk considering natural preconditions and land use. The mapping could be further developed to monitor the soil erosion risk by the use of real-time data (e.g. satellite and radar data, land use information, and topography data) as well as by mapping support and management practices via the P-factor.

Such monthly erosion risk maps are of high importance for policy, soil scientist, environmentalists, and agronomists because they serve as a knowledge base to answer the question about where and when soil damage might occur on Swiss grassland. RUSLE does not include snow induced processes, so the overall soil loss might not necessarily be greatest in the summer, but our modelling confirms that highest damage due to grazing (low C factor) and high rainfall erosivity leaves the soils damaged and vulnerable after the summer, leading to a high risk of snow induced processes. As each factor is developed individually, it uses key information from different disciplines and can be merged with other sources of information to enable more targeted interventions e.g. for soil and environmental protection, hazard mitigation, land use change, and agricultural management.

Based on the monthly maps, a controlled spatial and temporal soil erosion protection strategy, such as a change in stocking rates for specific hotspots and periods or the fencing of hotspots, is now feasible. The approach for grasslands with a particular focus on the Alpine conditions could serve as a prototype for erosion mapping on grassland in other grassland dominated regions and countries like Austria, Germany, Italia, Slovenia, or France and would help to protect the unique nature of these grasslands.

Software

The monthly maps of soil erosion by water for Swiss grasslands are a product of statistical, remote sensing, geoinformation and cartographic approaches which are described in detail in the corresponding literature of each erosion factor (Table 2).

The combination of the five factors of monthly soil erosion maps was realized in ESRI ArcGIS (v 10.3.1) likewise the layout of the map was designed in the same commercial software. R (v 3.4.3) and RStudio (v 1.1.423) were used for statistical analysis and interpretation of the erosion maps and underlying data.

Geolocation information

Country: Switzerland; scale: national scale; coordinates: Top-Left N 47.808463° E 5.955889° and Bottom-Right N 45.817967° E 10.492063°.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

Raw data were generated at Swisstopo, MeteoSwiss, Swiss cantonal offices, Copernicus Global Land Services, European Space Agency ESA, and National Aeronautics and Space Administration NASA. Derived data supporting the findings of this study are available from the corresponding author SS on request.

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