Soil & Tillage Research 213 (2021) 105155

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Summable C factors for contemporary soil use

Karl Auerswald [a,b,*], Florian Ebertseder [b], Karin Levin [b], Ye Yuan [c], Volker Prasuhn [d], Nils Ole Plambeck [e,f], Annette Menzel [c], Max Kainz [g]

[a] Technical University of Munich, Aquatic Systems Biology Unit, TUM School of Life Sciences, Mühlenweg 22, Freising, 85354, Germany
[b] Bavarian State Research Center for Agriculture, Institute for Organic Farming, Soil and Resource Management, Lange Point 6, Freising, 85354, Germany
[c] Technical University of Munich, Ecoclimatology, TUM School of Life Sciences, Hans-Carl-von-Carlowitz-Platz 2, Freising, 85354, Germany
[d] Agroscope, Water Protection and Substance Flows, Reckenholzstrasse 191, Zurich, 8046, Switzerland
[e] State Office for Agriculture and Rural Areas. Department 31 "Crop Production and Organic Farming", Naumburger Straße 98, Jena, 07743, Germany
[f] German Environment Agency (UBA), Wörlitzer Platz 1, Dessau-Roßlau, 06844, Germany
[g] Technical University of Munich, Chair of Organic Agriculture and Agronomy, TUM School of Life Sciences, Liesel-Beckmann Str. 2, Freising, 85354, Germany

ARTICLE INFO

Keywords:
Crop development
Erosion modeling
Maize
Small grain
Climate change

ABSTRACT

Crop cultivation, crop stages and the seasonal distribution of rainfall erosivity are continuously changing in response to changes in climate and socio-economic conditions. Therefore, the crop and cover factor (C factor) of the (Revised) Universal Soil Loss Equation should also be adjusted continuously. Within the framework of the (R) USLE, C factors can only be calculated for crop rotations. However, for large-scale and regional modeling of soil erosion on arable land and targeted subsidy schemes for the implementation of soil protection measures, C factors are required that quantify the effect of individual crops and management options on the risk of soil erosion. We therefore develop a method for deriving summable C factors that can easily be combined to derive C factors for crop rotations. These summable C factors also account for carry-over effects that influence the risk of soil erosion in subsequent crops. Using the latest data on the temporal distribution of rain erosivity and approximately 3.5 million observations of crop stages, summable C factors were derived for 57 crops and crop management options, including double cropping, which is currently becoming more prevalent in temperate areas. These C factors apply for Germany. However, the regional variation of summable C factors within Germany was small and comparison with Swiss data indicated that our summable C factors will also apply in neighboring countries in Central Europe. Changes in the seasonal distribution of rain erosivity and in crop development due to climate change caused some convergence of the summable C factors for different crops, i.e. the C factors for crops where the risk of soil erosion potential had previously been low increased, while for those crops where the risk of erosion had previously been high the C factors decreased. Of the arable crops, potatoes had by far the highest summable C factor, whereas sod-forming crops had negative summable C factors, leading to low C factors for crop rotations. The sod crops seem to be largely responsible for the low level of soil erosion found on many organic farms and in Switzerland, where sod crops account for a large share of arable land.

1. Introduction

Soil use is always strongly influenced by local environmental conditions, such as soil capacities and the local climate, and by socio-economic constraints including political directives. The remaining decision space is then used by farmers according to their personal preferences and contexts. All three constraints to soil use, namely environmental, socio-economic and personal, are currently changing extraordinarily quickly compared to the pace of change in previous centuries or millennia. For example, as the climate changes other crops and cropping options become feasible. Soybeans, which were not cultivated at all in Germany only 20 years ago, were ranked 13 in the list of the most important crops in 2019 (Destatis, 2020) (for scientific names of all crops see Tables 1 and 3). Crop cultivation techniques have also changed. Climate change has induced changes in phenological development (Dose and Menzel, 2004; Menzel et al., 2020) that make it necessary to adjust the timing of agricultural operations such as sowing or harvesting, even though the response by farmers to climate change seems to be delayed (Menzel et al., 2006; Estrella et al., 2007).

The model most often used to predict the long-term annual mean of

* Corresponding author at: Technical University of Munich, Aquatic Systems Biology Unit, TUM School of Life Sciences, Mühlenweg 22, Freising, 85354, Germany.
E-mail address: auerswald@wzw.tum.de (K. Auerswald).

https://doi.org/10.1016/j.still.2021.105155
Received 19 April 2021; Received in revised form 1 July 2021; Accepted 16 July 2021
Available online 2 August 2021

sheet and rill erosion is the (Revised) Universal Soil Loss Equation (R) USLE (Wischmeier and Smith, 1978; Renard et al., 1997). Within the (R) USLE framework, the erosion potential of a crop rotation is mapped by the C factor, which also includes the influence of crop management options. The C factor quantifies the combined effect of the seasonal variation in rain erosivity and crop cover on soil erosion. Both factors determine whether an erosive rain is likely to hit a poorly protected soil surface or whether it will be intercepted before it reaches the surface. This implies that temporal changes in crop development alter the erosion potential of the crop rotation. Moreover, climate change has a strong influence on the seasonal distribution of erosive rainfall (Auerswald et al., 2019a). The influence of these two concurrent changes on the erosion potential of crops is complex. The erosion potential of crops could either increase or decrease, and thus the relative importance of crops in terms of soil erosion could also change. This invalidates established rules about the erosion relevance of crops (Auerswald and Menzel, 2021).

In addition to these changes in the natural environment, socio-economic conditions also change rapidly and these changes have become faster in recent decades; globalization exposes individual farmers managing a small parcel of land to a barrage of political and economic decisions happening around the world. This means that farmers have to adapt rapidly to the current market situation. As a result, the vast majority of farmers today are no longer able to maintain traditional crop rotations, but make short-term decisions about land use, leading to complex and unsystematic crop sequences (Leteinturier et al., 2006; Waldhoff et al., 2017; Stein and Steinmann, 2018). Technical and technological developments have enabled and accelerated the abandonment of traditional crop rotations (Stein and Steinmann, 2018; Tariq et al., 2019); pesticides reduce the disease and pest pressure resulting from inadequate crop rotations. With increasing machine size and power, crop management operations can be carried out on large areas within narrow time frames, which eliminates, at least partly, the need to attenuate work peaks using crop diversification.

The widespread abandonment of consistent crop rotations is not only disadvantageous from an ecological point of view but is also rather unfortunate for erosion prediction and planning. Within the (R)USLE framework, the erosion potential can only be quantified for rotations and not for individual crops - although this erroneous simplification is even found in scientific literature (e.g. Folly et al., 1996; Cebecauer and Hofierka, 2008). This is because the (R)USLE is used to calculate the long-term, rather than short-term, mean soil loss. There are two further important reasons as to why the erosion potential can only be determined for rotations and not for crops. First, there are sometimes large temporal gaps between two subsequent crops that cannot be assigned to either the first or the second crop because the gap would be different if one of the crops was substituted by a different crop. Take, for instance, the crop sequence fall barley followed by maize. The fall barley is harvested in July; the subsequent maize crop is then not sown until late April. Hence, there is a temporal gap of eight months, or two thirds of the entire year, between the two crops. During this time, 49 % of the total annual erosivity falls in Germany (Auerswald et al., 2019a). This period cannot be assigned to either barley or to maize but only to a rotation that results in this specific sequence of crops. The large variability between fields due to different cultivation techniques occurs mainly during this phase (Büchi et al., 2016). Different scenarios are conceivable for land management during this large temporal gap between subsequent main crops: one option is that during this time the soil remains almost uncovered. Instead, a frost-intolerant cover crop could be grown during this period, which is freeze-killed during winter. Subsequently maize can be drilled directly into dense mulch cover. In this case, there would then be full soil cover for about two years from fall barley sowing until maize harvest. This excellent erosion protection (Kainz, 1989) would not be achieved with either maize or fall barley monocultures, nor in a rotation of fall grain. Hence, the advantage of mulch-based direct drilling of maize cannot be quantified by only looking at maize or fall barley individually but can only be attributed to a rotation. A rotation of maize-maize-fall barley-fall barley thus differs considerably in erosion potential from a rotation of maize-fall barley, even though the proportions of maize and fall barley are identical. Mulch-based direct drill can be applied every second year in the second rotation, while in the first rotation this is only possible every fourth year.

The second reason as to why the erosion potential can only be assessed for crop rotations and not for individual crops are carry-over effects, which influence the soil loss in subsequent crops. The most important crops that have carry-over effects are root crops, and clover-grass and other sod-forming crops. Root crops such as potatoes or sugar beet, due to intensive soil disturbance during harvesting, leave behind soil that is highly susceptible to erosion. For example, soil loss in fall grain is considerably higher when this grain crop follows a root crop such as potato than when it follows a different row crop such as maize. Fiener and Auerswald (2007) were able to demonstrate that most of the high erosion potential of potatoes resulted from the subsequent fall grain and not from the potato year.

Carry-over effects can also have the opposite effect, as is the case for sod-forming crops that are typically found on organic farms because the legume component in these crops is an important source of nitrogen; in Switzerland, however, they are also frequently grown on conventional farms (Prasuhn, 2012, 2020). Sod-forming crops can reduce erosion for as much as a further two years (Wischmeier and Smith, 1978) but the absolute size of the effect depends on the subsequent crop. If a crop with low erosion risk follows, the carry-over effect will not make much difference to the erosion risk, whereas a large effect can be expected if an erosion-prone crop follows. The carry-over effect develops because soil aggregates stabilize and organic matter content and earthworm populations increase due to the long period of time without tillage (Pena-Yewtukhiw et al., 2017; Edwards and Bohlen, 1996). Furthermore, an intensive rooting of the topsoil takes place because the deep-reaching, primary, seed-borne roots are increasingly replaced by secondary, stem-borne roots (Chochois et al., 2015). In sods, 70 % of the total root length is located in the top 7 cm of a soil (Matthew et al., 2001), which is consistent with the depth distribution of water uptake (Hirl et al., 2019). This is because cutting a sod crop initiates regrowth that can only happen by building new phytomers. A phytomer is the functional unit of grass growth consisting of a leaf blade, a sheath, a leaf node and one to two roots attached to each leaf node (Matthew et al., 2001). Consequently, cutting leads to new nodal roots starting at the soil surface. Roots belonging to a phytomer usually begin to grow after the leaf blade of this phytomer is removed either by grazing, cutting or senescence. These roots usually have a lifespan of about two years after the removal of the leaf blade (Matthew et al., 2001; Yang et al., 1998). Consequently, it takes at least two to three years after the first cut of the sod crop until full nodal root density is reached, when the rate of root formation is equal to the rate of root senescence. The full potential of sod-forming crops to reduce erosion can therefore only be realized if sods are maintained for more than two years. This is in line with experimental findings (Pena-Yewtukhiw et al., 2017) and practical experience (Jenkins, 2020), which confirm that it takes two years of sod in mixed farming to observe the full effect on earthworms and soil structure.

To deal with the problem that C factors can only be calculated for rotations but that rotations are likely to continue to change, we develop a method for determining the C factors of individual crops, while at the same time taking into account the effects that result only from the combination of these crops within crop rotations. These C factors can then be added together according to the proportion of each crop. This also means that regional C factors can now be calculated, which to date has not been possible within the (R)USLE framework. Perennial crops, for which the interaction with preceding and succeeding crops is negligible, have not been included in this analysis.

The C factors that we derive apply for all of Germany. We will show that differences in temperature between regions only have a marginal influence on the C factors, partly because temperature differences are small and partly because their effects cancel each other out. Crops and crop management also depend on socio-economic conditions, which are constrained by political settings. Similar conditions, however, also exist in other countries in Europe. The second reason for restricting our analysis to Germany is that climate change has changed the seasonal variation of rain erosivity and crop development, which both influence the C factor. This invalidates old data. These seasonal variations in rain erosivity have only recently been measured for Germany (Auerswald et al., 2019a; Auerswald and Menzel, 2021). However, to the best of our knowledge, similar evaluations of current seasonal variation do not exist for other countries. Nevertheless, given that the seasonal variation in rain erosivity shows a similar pattern across different regions of Germany (Auerswald et al., 2019a) and Switzerland, Poland, Belgium or the Netherlands, the variation in crop development in these countries should also be within the range of variation observed for the German regions. Hence, we expect that our analysis will also apply to neighboring countries.

2. Material and methods

The erosion potential of a crop sequence, namely the C factor from the USLE, results from the combination of the seasonal variation of two parameters, namely the seasonal variation of the rain erosivity index *REI* and the seasonal variation of the soil protection by crop and plant residues quantified as the soil loss ratio *SLR*. Mathematically this is calculated as (Wischmeier, 1960):

$$C = \sum_{i=1}^{n \cdot t} REI \times SLR \Big/ t \tag{1}$$

REI is the relative fraction of the total long-term mean annual erosivity that falls within a period of interest. The seasonal distribution of *REI* was recently determined from a large radar rain dataset (Auerswald et al., 2019a) and was taken from this source. To quantify the influence of climate change, we additionally used the historic rain erosivity distribution from Schwertmann et al. (1990). Until recently this distribution was used to calculate C factors for Germany (DIN, 2017) although it is based on measurements from only 18 rain gauge stations.

SLR is the soil loss of a particular crop and soil condition relative to the soil loss of a long-term seedbed under otherwise identical conditions. *SLR*s are usually determined from long-term soil loss measurements or rainfall simulation experiments, or by calculation from soil and crop properties using a subfactor approach (e.g. Renard et al., 1997). We used the *SLR*s as reported by Auerswald and Kainz (1998) with one exception, namely potatoes, for which the *SLR*s from Prasuhn and Blaser (2018) were used. The *SLR*s by Auerswald and Kainz (1998) were mainly determined from rainfall experiments for arable crops like small grains, maize and sugar beet (Auerswald, 1985a, 1985b; Kainz, 1989), while those for less frequently grown crops were determined from subfactors. *SLR*s are given in Table A1 in the appendix. These *SLR*s were used in accordance with the German standard for application of the USLE (DIN, 2017).

The variable *t* is the length of a rotation in years. By dividing by *t*, the C factor quantifies the mean annual susceptibility to erosion over the entire crop rotation. The variable *n*, finally, is the number of temporal stages in a cropping year, starting with primary tillage and ending with the next primary tillage. Wischmeier and Smith (1965) suggested splitting each cropping year into six crop stages. These crop stages are rather short when soil protection by soil cover changes quickly, e.g. during early growth, and rather long for periods of little change, e.g. when vegetative crop growth is completed. We used the six crop stages as suggested by Wischmeier and Smith (1965), which comprise 1) primary tillage until seedbed preparation (abbreviated F for fallow), 2) seedbed preparation to 10 % crop cover (SB), 3) 10 % to 50 % crop cover (P10 %), 4) 50 % to 75 % crop cover (P50 %), 5) 75 % crop cover until harvest (P75 %), and 6) harvest until next primary tillage (H).

The date when one crop stage finishes and another starts is thus essential for the selection of *REI* and *SLR*. The dates from Schwertmann et al. (1990) were used for the historic situation of about 1970 to 1980. Meanwhile, climate change has accelerated crop development, particularly for crops with C4 photosynthesis due to their larger temperature sensitivity, but also for C3 crops (Auerswald and Menzel, 2021). The German Meteorological Service (Deutscher Wetterdienst, DWD) has been running a phenological observation program since 1951 called “annual reporters” (Kaspar et al., 2014), which also includes arable crops. The first occurrences of generally six to eight important phenological stages (for a detailed description see DWD, 2014) are recorded for a total of 6665 locations scattered across Germany (see Fig. A1 in the appendix). However, there were only about 1500 recordings of a particular crop stage and crop per year (higher numbers for the most frequent crops and for sowing and harvest). This is because not all crops can be found everywhere in every year and because some annual reporters may have stopped their work without being replaced, while others may have changed location. These time series exist for maize, potato, (sugar) beet, fall small grain (wheat, barley, rye, canola), spring cereals (wheat, barley, oats) and for sunflower. We used the time series between 1960 and 2020 (between 21 530 and 96 095 individual records of a particular phenological stage; on average 63 660) to capture possible trends. We extrapolated the resulting linear trends from the last observations in 2020 until 2025, although in most cases this changed the dates by less than one day compared to the last year of observation. The year 2025 was chosen because rain erosivity (R factor) changes rapidly (Fiener et al., 2013; Auerswald et al., 2019a) and can no longer be regarded as a site constant, as it is in the USLE. Due to accelerating climate change, if older data is used to calculate the R factors, this will underestimate both the current and future erosion risk. Therefore, Auerswald et al. (2019b) extrapolated the most recent R factor data in Germany (from the 1950s to 2019) with a second order polynomial to yield the R factor for the pivotal year 2025. These data will be used for soil loss calculations until newer meteorological data enable extrapolation to a later pivotal year. The calculation of C factors for 2025 should ensure consistency among USLE factors, even if the influence on crop dates is negligible.

With the exception of sowing and harvesting, the phenologically defined crop stages do not exactly correspond to the crop stages defined by soil cover, as required for the calculation of the C factor. To address this discrepancy, we used the approach from Auerswald and Menzel (2021): we selected the phenological crop stages that were closest to soil cover crop stages in the 1980s, when the crop stages were determined by Schwertmann et al. (1990). In most cases, phenological and soil cover stages were only a few days apart. For instance, the 10 % soil cover stage for maize was reached only three days before elongation started, while the 75 % soil cover date was reached only one day earlier than the average start of tasseling. We then assumed that the temporal change to the phenological stage also applied to the soil cover stage. Furthermore, we had to take into account that each annual reporter only recorded the first occurrence of a certain phenological crop stage, such as sowing or harvesting, in their respective area of observation, whereas the typical date is required for the calculation of the C factor. We therefore added 7 d to the mean dates of sowing and harvesting, assuming that these agricultural operations in the small observation area (radius of approximately 2 km, situated within one landscape; DWD, 2014) of an individual reporter are usually completed within 14 days.

No data were available from annual reporters or from Schwertmann et al. (1990) for several crops. In these cases, the occurrence of crop stages was estimated by experts from different regions (see authors and acknowledgement) with a broad knowledge of crop management.

2.1. Sod-forming crops

The calculation of C factors of rotations containing sod-forming crops (grass, clover-grass, alfafa-grass, clover and others) has to consider that they can be cultivated in various ways that differ in the type of establishment and in the length of use. Sod-forming crops may either be established by undersowing in a preceding small-grain crop (usually between the end of April to mid-May) or by conventional sowing (usually mid to late August after small-grain harvest). The length of use ranges from only one to several years. Wischmeier and Smith (1978) assumed that combined effects of sod-forming crops on aggregate stability, soil fauna and topsoil root density and in turn on soil erosion lasts for two years but that its strength gradually reduces over time. We used their carry-over factors (their table 5D) and assumed that there is no sod effect with conventional sowing in combination with only one year of use. The reason is that the period without soil disturbance is no different to that for other annual crops and the replacement of seminal roots by nodal roots may not have even started. The full carry-over effect is achieved if the sod crop is used for at least two full years, resulting in the highest possible root density in the topsoil. If a sod crop, established using undersowing, is only used for one full year, this would mean there is no tillage for about two years, starting from the sowing of the grain crop until the inversion of the sod crop. In this case, we assumed that a sod effect has already developed but will only last one instead of two years. Hence, we used the carry-over factors for the second year from Wischmeier and Smith (1978).

2.2. Double cropping

In future, increasing temperatures may allow double cropping, even in previously temperate areas. One of the first applications of double cropping in Germany can be found on biogas farms (Graß et al., 2013; Herrmann, 2013). These farms grow a (C3) fall grain, usually fall wheat or fall triticale, sometimes combined with a grain legume like fall pea or vetch, which is followed by (C4) maize. This combines the higher quantum-use efficiency of plants using C3 photosynthesis at low temperatures with the higher quantum yield of C4 plants at high temperatures. The fall grain is harvested before reaching maturity as whole plant for silage (WPS). The time frame within which the immature fall grain can be harvested is quite long. However, in practice, harvesting usually takes place between 10 May and 20 June. Thus, not a single C factor but a range of C factors may result. It is therefore necessary to know how the harvest date of the WPS grain influences the C factor. We therefore calculated the C factor for WPS grain-maize rotations covering the whole range of possible cultivation and harvesting dates: from the earliest possible date for the WPS harvest and for regular maize sowing (end of April) to the latest possible date for a regular grain harvest (end of July). This required an estimation of how crop stages change with delayed sowing at higher temperatures. Average air temperatures for Germany for the years 1992–2019 increased from the end of April (daily long-term mean 7.2 °C) to the end of July (19.2 °C) in accordance with a square function ($y = 9.36\ 10^4 \times D^2 + 0.39 \times D – 20.9$; $r^2 = 0.9242$, $n = 118$ d; data taken from the DWD, 2021; D is day of the year). The period between sowing and elongation of maize corresponds to the maize SB period (Auerswald and Menzel, 2021). Using the annual mean dates of maize sowing (in total 68 749 observations) and correlating these dates with the mean temperatures in April and May led to a very highly significant correlation with a slope of -3.05 d °C^{-1} (see Fig. A2 in the appendix). An analogous correlation for elongation (26 825 observations) led to a very highly significant slope of -7.33 d °C^{-1} (see Fig. A2). Due to the steeper slope of elongation, the period between sowing and elongation decreased very highly significantly by -3.24 d °C^{-1} with increasing mean temperature in April and May. The same slope was assumed for the SB period to estimate the effect of delayed sowing. The subsequent crop stages were adjusted accordingly. Finally, crop stage dates for every day of a delayed sowing of maize were available and an annual C factor for a typical maize rotation with double cropping, consisting of a green harvested fall cereal and a subsequent maize crop, was calculated.

2.3. Specialty crops

It was not feasible to apply Eq. (1) to include rarely grown specialty crops such as vegetables, because not enough was known about how the crop stage periods may have changed due to climate change for these crops. Provisionally, a regression between old (historic) and current C factors was calculated for those rotations where all data for the historic situation (from Schwertmann et al., 1990, and DIN, 2017) were available. This regression was then applied to the C factors of rotations including 31 specialty crops taken from Auerswald and Kainz (1998). This approach assumes that changes in these specialty crops are similar to those in the main crops. This will not apply in all cases, and the correct calculation of C factors is recommended for the often very specific situation in which specialty crops are grown.

2.4. Data analysis

C factors were calculated for a total of 33 (arable) crops/management options combined in 261 rotations and a total of 935 crop years. Crop stage dates were adjusted for each rotation according to the sequence of crops and typical agricultural practice. For example, in a sequence of a crop with a late harvest date and a subsequent crop with an early sowing date, either an earlier harvest date or a later sowing date or both were chosen until all necessary field operations were possible and corresponded to typical farming behavior.

This yielded crop rotation C factors but not C factors for individual crops that could be combined arbitrarily. We call them summable C factors, γ (the third letter in the Greek alphabet analogous to C, indicating the generic character of summable C factors), in order to distinguish summable C factors from C factors of rotations, crop sequences or monocultures that cannot be combined. The C factor of a specific field, farm or region with m different crops can then be calculated from the fractions of the individual crops f_i and their summable C factors γ_i:

$$C = f_1 \times \gamma_1 + f_2 \times \gamma_2 + \ldots + f_m \times \gamma_m \tag{2}$$

To disaggregate C factors of rotations into summable C factors, we combined all data and used multiple regression analysis with the intercept set to zero:

$$C \times t = a_1 \times x_1 + a_2 \times x_2 + \ldots + a_n \times x_z \tag{3}$$

C is the C factor of a rotation and t is the number of years of a specific rotation. The variables x_1 to x_z denote how many years each of z crops were present in this rotation (for most crops x will be zero in a specific rotation). The slopes a_1 to a_z that result from the regression analysis are then the desired γ for crops 1 to z. All the effects of a particular crop, even if they occurred in the preceding crop because crop stage periods H and F changed or did not even occur, as is the case with undersowing, were thereby attributed to the causal crop. In addition, all effects in subsequent crops due to carry-over effects were attributed to the causal crop. Therefore, and in contrast to normal C factors, γ does not reflect the erosion situation during the period in which the crop is grown, but the erosion effect of the crop over the entire sequence of crops. Negative summable C factors are therefore possible if a crop reduces soil loss in subsequent crops, while the C factors of crop rotations must always be greater than zero.

In the appendix we provide an example of the entire calculation procedure from the calculation of C factors for individual crop rotations according to the USLE to the disaggregation into summable C factors.

2.5. Statistics

Statistical analysis was carried out with R (R Core Team, 2019), CoStat (CoHort Software, Monterey, USA) and Excel (Microsoft, Redmond, USA). The disaggregation of rotational C factors using multiple regression included a twofold cross-validation, which is the most pessimistically biased cross-validation (Kohavi, 1995). It splits the

Table 1
Summable C factors γ of different crop groups according to crop type; 95 % CI denotes the 95 % confidence interval; cases are the number of calculated rotational positions of the specified crop in a total of 261 different rotations.

No.	Common name	Scientific name	γ	+/- 95 % CI	Cases	Remark
	Fall-sown small grain					
1	Canola	*Brassica napus* L.	0.087	0.018	12	1
2	Wheat	*Triticum aestivum* L.	0.085	0.007	226	
3	Triticale	×*Triticosecale*	0.073	0.016	26	2
4	Rye	*Secale cereale* L.	0.071	0.021	11	3
5	Barley	*Hordeum vulgare* L.	0.070	0.006	114	4
	Spring-sown small grain					
6	Oats	*Avena sativa* L.	0.117	0.019	13	
7	Wheat	*Triticum aestivum* L.	0.116	0.016	18	5
8	Barley	*Hordeum vulgare* L.	0.076	0.012	33	
	Row crops					
9	Potato	*Solanum tuberosum* L.	0.376	0.011	53	
10	WPS + maize	*Zea mays* L.	0.261	0.009	44	6
11	Sunflower	*Helianthus annuus* L.	0.261	0.021	9	
12	Silage maize	*Zea mays* L.	0.252	0.008	66	
13	Grain maize	*Zea mays* L.	0.245	0.011	30	
14	Sugar beet	*Beta vulgaris* L.	0.181	0.017	16	7
15	Sorghum	*Sorghum bicolor* (L.) Moench	0.148	0.011	16	
	Row crops, direct drill					8
16	Sugar beet	*Beta vulgaris* L.	0.051	0.026	6	
17	Silage maize	*Zea mays* L.	0.050	0.024	7	
18	Grain maize	*Zea mays* L.	0.048	0.020	8	
19	Sunflower	*Helianthus annuus* L.	0.040	0.028	5	
	Row crops, mulch till					9
20	Silage maize	*Zea mays* L.	0.166	0.028	6	
21	Sunflower	*Helianthus annuus* L.	0.164	0.028	5	
22	Grain maize	*Zea mays* L.	0.156	0.028	9	
23	Sugar beet	*Beta vulgaris* L.	0.119	0.020	11	
	Grain legumes					
24	Soybean	*Glycine max* L. Merrill	0.241	0.023	8	
25	Broad bean	*Vicia faba* L.	0.178	0.015	26	
26	Field pea	*Pisum sativum* L.	0.141	0.019	16	10
	Sod crops					
27	First year, conventionally sown		0.039	0.018	28	11
28	First year, undersowing		−0.077	0.018	28	11
29	Second year		−0.136	0.021	32	11
30	Third and subsequent years		−0.013	0.022	18	11
31	Default value		−0.065			12
	Specialty crops					
32	Buckwheat	*Fagopyrum esculentum* Moench	0.189	0.015	23	
33	Fiber hemp	*Cannabis sativa* L.	0.117	0.011	16	
34	Grain hemp	*Cannabis sativa* L.	0.117	0.015	23	

Remarks:
1. similar: turnip rape *Brassica rapa* L. subsp.*silvestris*, field mustard *Brassica rapa*subsp.*oleifera*.
2. including mixed crops based on triticale like triticale-fall pea.
3. including emmer (*Triticum turgidum* L.), einkorn (*Triticum monococcum* L.), spelt (*Triticum* spelta L.), durum wheat (*Triticum durum* Desf.) and mixed crops based on rye like rye-vetch (*Vicia spec*.).
4. also fall oats.
5. also spring rye, spring triticale, spring spelt, spring emmer, spring einkorn and durum wheat.
6. double cropping of a WPS (whole plant silage) fall grain followed by maize.
7. similar: fodder beet *Beta vulgaris*subsp.*vulgaris*, rutabaga *Brassica napus*subsp.*rapifera* Metzg.
8. direct drill requires at least 30 % cover by mulch material after seeding; otherwise use values for mulch tillage.
9. mulch tillage: a cover crop is sown after the preceding crop. This cover crop is left over winter until the subsequent row crop is sown using only shallow secondary cultivation, thereby leaving some crop residues on the soil surface.
10. similar: lentil *Lens culinaris* Medik.
11. grass, clover-grass, alfafa (*Medicago sativa* L.)-grass, white clover (*Trifolium repens* L.) and other mixtures containing grass or white clover.
12. the default value can be used for calculation of regional C factors from cropping statistics where data on how sod crops are integrated into rotations are not available. It assumes that one fifth is the first year of conventionally-sown sod, one fifth is the first year of undersown sod, two fifths are second-year sods and the remaining one fifth are sods in their third year or older. This value should not be used if more about the rotational position of sod crops is known.

dataset randomly into two mutually exclusive subsets and uses one half to derive the summable C factors and the other half to validate them.

3. Results and discussion

3.1. Comparison of historic and current rotational C factors

The mean rotational C factors hardly changed (0.120 vs 0.121) between the historical situation in the 1980s and the current situation in the 2020s. The greater share of the rain erosivity index during the dormant season led to a 20 % increase in the average to 0.144, but the faster growth of row crops in the spring compensated for this. As a result of both changes, the erosion potential of fall-sown crops increased while the erosion potential of spring-sown crops decreased. This caused a contraction in the range of rotation C factors. In general, the relative position of rotations did not change, as indicated by an r^2 of 0.9552 for the regression:

$$C_{present} = 0.66 \times C_{historic} + 0.042 \quad (4)$$

Table 2
Estimation of summable C factors γ for crops or crop management options not included in Tables 1 and 3, or for crop development conditions that differ strongly from average conditions.

Crop / management	Equation	Variables, remarks
Fall-sown small grain	$\gamma = 0.1492 \times \left(\frac{D_{10\%}}{100}\right)^2 - 0.8573 \times \frac{D_{10\%}}{100} + 1.3005$	$D_{10\%}$ is the day of the year when 10 % crop cover is achieved
Spring-sown crops	$\gamma = 0.173 \times W + 0.099 \times \frac{D_{10\%}}{100} - 0.054$	$D_{10\%}$ is the day of the year when 10 % crop cover is achieved, W is row width in m
Mulch tillage of row crops	$\gamma_{mulch} = \gamma_{conv} - 0.083$	SD of the constant is 0.015
Direct drill row crops	$\gamma = 0.047$	SD is 0.005

Table 3
Summable C factors γ from disaggregation of rotational C factors with specialty crops given by Auerswald and Kainz (1998), after adjustment for climate change according to Eq. (4).

No.	Scientific name	Common name	γ
35	*Allium cepa* L.	Spring onion	0.365
36	*Allium cepa* L.	Fall onion	0.465
37	*Amaranthus sp.*	Amaranth	0.245
38	*Calendula officinalis* L.	Calendula	0.165
39	*Camelina sativa* (L.) Crantz	Camelina	0.085
40	*Carthamus tinctorius* L.	Safflower	0.085
41	*Cichorium intybus*var. *sativum* L.	Chicory	0.265
42	*Coriandrum sativum* L.	Coriander	0.145
43	*Crambe abyssinica* (Hochst. ex R.E.Fr.) Prina	Crambe	0.085
44	*Cucumis sativus* L.	Cucumber (gherkin)	0.365
45	*Cucurbita pepo* var. *styriaca* L.	Seed pumpkin	0.225
46	*Daucus carota* subsp. *sativus* (Hoffm.) Schübl. & G.Martens	Carrot	0.265
47	*Euphorbia lathyris* L.	Caper spurge	0.225
48	*Foeniculum vulgare* (L.) Mill.	Fennel	0.305
49	*Helianthus tuberosus* L.	Jerusalem artichoke	0.085
50	*Linum usitatissimum* L.	Fiber flax	0.105
51	*Linum usitatissimum* L.	Linseed	0.125
52	*Lupinus spp.*	Lupin	0.185
53	*Panicum miliaceum* L.	Common millet	0.145
54	*Papaver somniferum* L.	Breadseed poppy	0.165
55	*Petroselinum crispum* (Mill.) Fuss	Parsley	0.205
56	*Sinapis alba* L.	Mustard	0.085
57	*Sorghum* × *drummondii* (Steud.) Millsp. & Chase	Sudan grass	0.225

We did not include sod-based rotations or double cropping in this comparison, nor rotations for which the historic crop stage dates were not available. A change in the rain erosivity index or the growing period cannot cause any changes during the permanent cover of the sod years, and double cropping was not possible under historic conditions.

Our calculations assume that the *SLR*s from Auerswald and Kainz (1998) are still valid. They mainly result from measurements in the 1980s (Auerswald, 1985a, 1985b; Kainz, 1989) or from calculations applying the subfactor approach. The parameters required to calculate *SLR*s with the subfactor approach from the RUSLE (Renard et al., 1997) or RUSLE2 (Foster, 2008) do not suggest that the *SLR*s in Germany have changed since they were determined. However, this is based solely on subjective observations because systematic historical and current measurements of the RUSLE parameters are not available. A reassessment of *SLR*s under present conditions is thus advisable given the multitude of changes in agriculture since the *SLR*s were originally determined in addition to the potential effects of climate change. However, given that C factors or *SLR*s are often taken from sources stemming from other countries or even continents (e.g. Cebecauer and Hofierka, 2008), or often even going back to Wischmeier and Smith (1965) which includes data dating back to the 1930s, our *SLR*s have to be regarded as being more reliable.

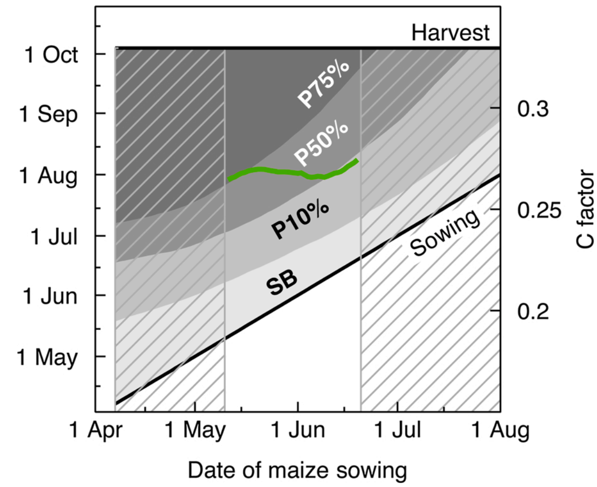

Fig. 1. Erosion-relevant growth stages of maize (different shades of gray) grown after a WPS crop, by sowing date (black line). The unhatched area denotes sowing dates typically found after a WPS crop. The start of the lines applies for maize when grown as a single crop. The green line is the C factor of WPS maize depending on when the maize is sown during the period suitable for double cropping.

Table 4
Crops as a proportion of the total arable land under rotational cropping systems (110 877 km²) in Germany, calculated based on official county statistics from 2016 (poorly-defined crop classes (4.5 %) were omitted); the national C factor was calculated by applying Eq. (2), i.e. the sum of the products $f_i \times \gamma_i$; fraction of total C is calculated as $(f_i \times \gamma_i)/0.124$.

Class in cropping statistics	Area fraction f_i (%)	γ_i	Fraction of total C (%)
Fall wheat including spelt and einkorn	28.2	0.085	19.4
Spring wheat	0.4	0.116	0.4
Durum wheat	0.2	0.116	0.2
Rye and mixed fall grain	5.1	0.071	2.9
Triticale	3.6	0.073	2.1
Fall barley	11.4	0.070	6.5
Spring barley	3.0	0.076	1.9
Oats	1.0	0.117	1.0
Spring mixed grain	0.1	0.103	0.1
Grain maize	3.8	0.245	7.4
Silage maize	19.3	0.252	39.2
Legumes, whole plant harvest	2.4	−0.065	−1.2
Arable grass	2.5	−0.065	−1.3
Potato	2.2	0.376	6.6
Sugar beet	3.0	0.181	4.4
Field peas	0.8	0.141	0.9
Broad beans	0.3	0.178	0.5
Lupines	0.3	0.185	0.4
Soybeans	0.1	0.241	0.3
Canola	11.9	0.087	8.4
Sunflower	0.2	0.040	0.0
Linseed	0.0	0.125	0.0
Hemp	0.0	0.117	0.0
National C	100.0	0.124	100.0

3.2. Summable C factors

Rotation C factors were calculated for 261 rotations comprising a total of 935 crop years. Disaggregation of rotation C factors resulted in summable C factors between -0.136 and 0.376, i.e. a range of 0.52, while the mean confidence interval for the individual crops was only 0.018.

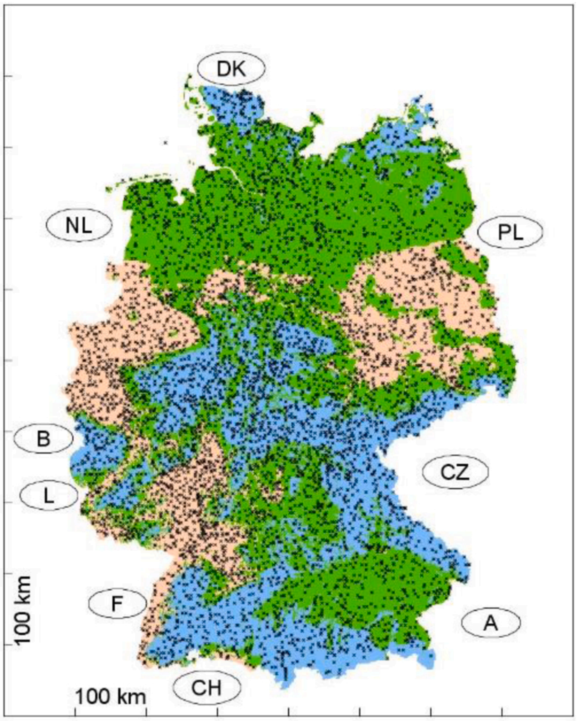

Fig. A1. Location of annual reporters recording phenological crop development (n = 6665). Light orange areas comprise the upper quarter of growing period temperatures (March to November), blue areas comprise the lower quarter of growing period temperatures in annual reporter locations. Letters in ellipses indicate neighboring countries (license plate abbreviations). Locations were taken from ftp://ftp-cdc.dwd.de/../climate_environment/CDC/observations_germany/phenology/annual_reporters/crops/historical/PH_Beschreibung_Phaenologie_Stationen_Jahresmelder.txt; temperature data were taken from ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/multi_annual/air_temperature_mean/8110/ (last access 15 Oct 2020).

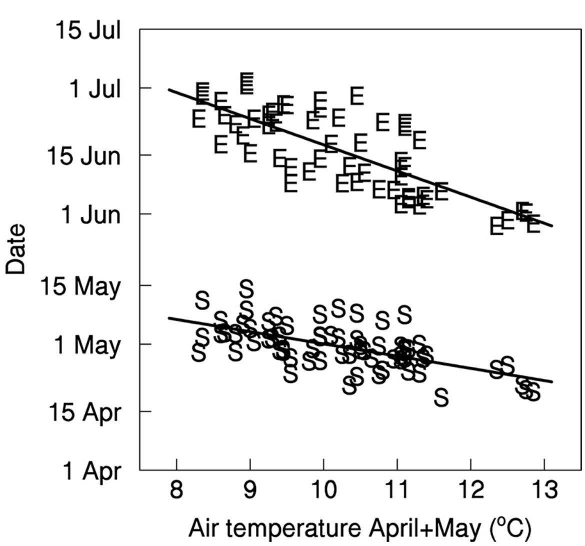

Fig. A2. Annual mean date of the start of sowing (S) and elongation (E) of maize versus mean air temperature in Germany in April and May in the respective year (years 1960 to 2020). Mean date of sowing was calculated from a total of 68 749 observations and mean date of elongation from 26 825 observations. r^2 of the regressions is 0.3761 (S) and 0.5914 (E).

Table A1
Soil loss ratios (%) depending on crop, cultivation type (conventional, mulch tillage and direct drill), crop and crop stage, and carry-over effect of sods (%); for abbreviations of crop stage periods see text. Data were taken from Auerswald and Kainz (1998); data given in italics were amended by applying the subfactor approach. The sod carry-over effect was taken from Wischmeier and Smith (1978).

	F	SB	P10 %	P50 %	P75 %	E
Small grain	32	46	38	3	1	2
Small grain after root crops	45	60	42	3	1	3
Silage maize	32	94	45	12	8.5	44
Silage maize, mulch till	*8*	*63*	*30*	*8*	*8*	*40*
Silage maize, direct drill	8	11	7	2	1	10
Grain maize	32	94	45	12	8.5	1
Grain maize, mulch till	*8*	*53*	*27*	*3*	*7*	*1*
Grain maize, direct drill	8	11	7	2	1	1
Potato	32	*200*	*50*	5	10	150
(Sugar) beet	32	85	45	5	3	44
(Sugar) beet, mulch till	*8*	*57*	*30*	*3*	*3*	*40*
(Sugar) beet, direct drill	8	9	6	3	3	15
Soybean	32	85	45	5	7	30
Field pea	32	65	45	5	2	3
Sunflower	32	87	35	8	9	3
Sunflower, mulch till	*8*	*58*	*24*	*6*	*9*	*3*
Sunflower, direct drill	8	10	6	3	3	2
Faba bean	32	85	45	5	2	3
Buckwheat	32	44	35	3	2	3
Fiber hemp	32	50	40	4	1	35
Grain hemp	32	50	40	4	1	35
Sorghum	32	85	42	5	4	3
Sod crops[1)], direct seeding	32	85	40	3	1	0.4
Cover crop[2)], after moldboard plow		*42*	*38*	*3*	*1*	
Cover crop[2)], after cultivator		*11*	*7*	*2*	*1*	
Carry over effect of sod						
1st year after inversion	25	40	40	45	50	60
2nd year, fall cereals	60	60	60	70	85	95
2nd year, spring cereals	70	75	75	80	85	95
2nd year, row crops	70	80	80	85	90	95

[1]For sod crops established by undersowing in small grain, soil loss ratios for small grain were used for all crop stage periods including E, and 0.4 was used after the first harvest of the sod. Also for all following years of sod, independent of the type of establishment, 0.4 was used.
[2]After small grain.

This indicates that the summable C factors had a fairly high accuracy (Table 1). In addition, the most pessimistic two-fold cross-validation showed that rotational C factors estimated from independently determined, summable C factors correlated closely and could be determined with a Nash-Sutcliff modelling efficiency of 0.9906. The mean absolute deviation was 0.005, which indicated that the deviation for the rotation C factors calculated from summable C factors was about a quarter of the deviation of the summable C factors, because deviations of individual crops partly cancelled each other out.

The most striking result was that γ was negative for some sod crops because the carry-over effect was larger than the erosion during the sod year. For a conventionally-sown, annual sod crop, γ was about half as large as γ for fall small grain (0.039 vs 0.077), but for an undersown annual sod crop, the summable C factor was -0.077, for the second sod year it was -0.136 and for subsequent (third or more) sod years it was close to zero (-0.013).

The use of summable C factors is always subject to errors if a specific crop rotation has a large influence on the local risk of soil erosion. This particularly applies to rotations with sod crops. We will use a region where the fraction of sod crops is 10 % as an example. The required summable C factor of the sod crop can be either 0.039 if the sods are all conventionally-sown annual sods, or -0.077 if the sods are all undersown annual sods, or (0.039−0.136)/2 = -0.049 if the conventionally-sown sod is used for a second year, or (-0.077−0.136)/2 = -0.107 if the undersown sod is maintained for a second year. This leads to a total

Table A2
Crop stage dates and typical row widths; for abbreviations of crop stage periods see text.

	F	SB	P10 %	P50 %	P75 %	E	Row width (m)
Fall small grain							
Wheat + spelt	1. Oct.	9. Oct.	15. Nov.	20. Mar.	8. Apr.	4. Aug.	0.125
Rye	15. Sep.	3. Oct.	1. Nov.	1. Dec.	1. Mar.	3. Aug.	0.125
Barley	10. Sep.	27. Sep.	15. Oct.	15. Nov.	8. Mar.	15. Jul.	0.125
Triticale	23. Sep.	7. Oct.	1. Nov.	1. Dec.	1. Apr.	31. Jul.	0.125
Canola	1. Aug.	31. Aug.	19. Sep.	28. Oct.	25. Mar.	3. Aug.	0.125
Spring cereals							
Barley	15. Oct.	31. Mar.	22. Apr.	2. May	7. May	5. Aug.	0.125
Oats	15. Oct.	3. Apr.	24. Apr.	4. May	9. May	10. Aug.	0.125
Wheat	15. Oct.	5. Apr.	29. Apr.	9. May	14. May	21. Aug.	0.125
Row crops							
Maize	13. Oct.	5. Apr.	15. May	13. Jun.	4. Jul.	3. Oct.	0.750
Potato	15. Oct.	6. Apr.	16. May	4. Jun.	17. Jun.	16. Sep.	0.700
(Sugar) beet	30. Oct.	29. Mar.	23. May	5. Jun.	17. Jun.	22. Oct.	0.450
Soybean	30. Oct.	15. Apr.	30. May	20. Jun.	15. Jul.	1. Oct.	0.375
Field pea	20. Oct.	1. Apr.	1. May	1. Jun.	n.a.	1. Aug.	0.125
Specialty crops							
Sunflower	15. Oct.	15. Mar.	30. May	13. Jun.	28. Jul.	1. Oct.	0.450
Fava bean	15. Oct.	15. Mar.	8. May	6. Jun.	20. Jun.	30. Aug.	0.135
Fiber hemp	15. Oct.	31. Mar.	15. Apr.	25. Apr.	5. May	20. Aug.	0.125
Grain hemp	15. Oct.	5. May	15. May	30. May	10. Jun.	15. Sep.	0.125
Sorghum	15. Oct.	1. May	1. Jun.	25. Jun.	9. Jul.	5. Sep.	0.125
Buckwheat	15. Oct.	5. May	20. May	15. Jun.	30. Jun.	15. Sep.	0.250

n.a.: usually not reached.

Table A3
Example of the C factor calculation according to the USLE for a rotation of conventional silage maize (SMc), fall wheat (FW) and fall barley (FB). Date denotes the start of the respective period. DoY is the day of the year. The other abbreviations are given in the main text.

Crop	Period	Date	DoY	*REI*	*SLR*	*SLR* × *REI*
SMc	F	13. Oct.	286	0.169	0.320	0.054
	SB	05. Apr.	110	0.075	0.940	0.070
	P10 %	15. May	135	0.149	0.450	0.067
	P50 %	13. Jun.	164	0.115	0.120	0.014
	P75 %	04. Jul.	185	0.472	0.085	0.040
	H	03. Oct.	276	0.009	0.440	0.004
FW	F	07. Oct.	280	0.004	0.320	0.001
	SB	09. Oct.	293	0.056	0.460	0.026
	P10 %	15. Nov.	319	0.108	0.380	0.041
	P50 %	20. Mar.	79	0.014	0.030	0.000
	P75 %	08. Apr.	98	0.558	0.010	0.006
	H	04. Aug.	216	0.187	0.020	0.004
FB	F	10. Sep.	253	0.048	0.320	0.015
	SB	27. Sep.	263	0.039	0.460	0.018
	P10 %	15. Oct.	288	0.045	0.380	0.017
	P50 %	15. Nov.	319	0.101	0.030	0.003
	P75 %	08. Mar	67	0.428	0.010	0.004
	H	15. Jul.	196	0.422	0.020	0.008
$C_{total} = \Sigma(SLR \times REI) =$						0.393
$C_{annual\ mean} = C_{total}/3 =$						0.131

Table A4
Example of the variables in the multiple regression analysis and the resulting gammas for a small subset of six rotations with the crops silage maize either conventionally sown (SMc) or direct drilled in a mulch cover (SMd), fall wheat (FW) and fall barley (FB). The dependent variable is y, while x_1 to x_4 denote the independent variables.

Rotation	y C_{total}	x_1 SMc	x_2 SMd	x_3 FW	x_4 FB
SMc – FW – FB	0.393	1	0	1	1
SMc – FW – FW	0.412	1	0	2	0
SMc – SMc – SMc	0.763	3	0	0	0
SMd – FW – FB	0.207	0	1	1	1
SMd – FW – FW	0.217	0	1	2	0
SMd – FW	0.134	0	1	1	0
	gamma	0.254	0.060	0.078	0.065

range of 0.146 between the extremes +0.039 and -0.107. The maximum error of the total C factor in this case is one tenth of this range because sod crops contribute only 10 % to arable land use but this means it could still be as high as 0.015. Summable C factors should therefore be selected with care. If information about the regional cultivation of sod crops is not available, the average of the summable C factors of sod crops should be used (i.e. the default value given in Table 1). The maximum error can then only be half of the total range and the likely error will be much smaller.

Summable C factors of (conventionally) fall-sown crops ranged between 0.070 (fall barley) and 0.087 (canola). They were lowest when sowing took place towards the end of September, while they were higher for earlier (e.g. canola) or later dates (e.g. fall wheat). At earlier sowing dates, a considerable part of the erosion-effective annual precipitation in autumn falls on unprotected soil, while with later sowing dates, crops enter the long dormant season with insufficient crop cover. This leads to parabolic behavior that can be described by the following equation ($r^2 = 0.9880$, $D_{10\%}$ is the day of the year when 10 % crop cover is achieved):

$$\gamma = 0.1492 \times \left(\frac{D_{10\%}}{100}\right)^2 - 0.8573 \times \frac{D_{10\%}}{100} + 1.3005 \quad (5)$$

The equation predicts that fall small grain crops have an especially low summable C factor when 10 % crop cover is reached around day 287 of the year (14 October). The influence of different sowing dates (due to farmer preferences or due to site-specific climatic conditions) on erosion risk can also be estimated using this equation. Fall rye, for instance, reaches 10 % soil cover around 15 October (Table A2 in the appendix). If it is sown earlier or later so that 10 % soil cover is reached 20 d earlier or later, the summable C factor increases from 0.071 to 0.075.

The summable C factors were slightly higher for spring-sown cereals than for fall small grain (between 0.076 for spring barley and 0.117 for spring oats), while summable C factors for row crops and grain legumes were two to three times as high (between 0.147 for sorghum and 0.376 for potato). The high summable C factor for potato is due to the concentration of runoff in the potato ridges (Chow and Rees, 1994), the poor soil cover (Büchi et al., 2016) and increased soil loss of the subsequent crop due to the sieving and compaction of the soil during harvest (Fiener and Auerswald, 2007). This is consistent with field observations (Evans et al., 2016; Prasuhn, 2020; Steinhoff-Knopp and Burkhard, 2018).

Looking at all 14 conventionally spring-sown crops (except for potatoes, which represent a particular set of circumstances), the summable C factor increased with the date 10 % crop cover was achieved ($\gamma = 0.0018 \times D_{10\%} - 82.429$, $r^2 = 0.4710$). In contrast, the date of seedbed preparation was irrelevant for the derivation of the summable C factors ($r^2 = 0.0009$) because the time required for the development of crop cover depended strongly on the course of germination and on row width ($\gamma = 0.22\ W + 0.103$, $r^2 = 0.7020$; W is row width in m). Combining the variables row width and date of 10 % crop cover in a multiple regression, however, resulted in a fairly accurate (mean confidence interval: 0.062) estimation of the summable C factor of a (unknown) spring crop ($r^2 = 0.8139$):

$$\gamma = 0.173 \times W + 0.099 \times \frac{D_{10\%}}{100} - 0.054 \quad (6)$$

This equation can also be used to predict how summable C factors of a particular spring-sown crop would change if row widths other than those assumed here (Table A2) are used, or if canopy development differs from the assumptions (e.g. if climatic conditions differ from the average). Eq. (6) predicts that the summable C factor for silage maize (0.252) would decrease by 0.043 if row width is reduced from 0.75 m to 0.50 m, while it would increase by 0.015 if unfavorable climatic conditions delay mean 10 % crop cover by 15 d. Both effects are independent of each other because during early growth, plants do not come into contact with other plants and thus a change in row width would not change $D_{10\%}$.

Row width and temporal development of the crop are irrelevant for mulch-based direct drill, as the mulch cover is not affected by these parameters. Therefore, the summable C factor varied by only a small amount (SD 0.005) around the mean of the different crops (0.047). This value can thus also be used for an unknown crop (except for potatoes) sown using direct drill. In contrast, if mulch till is used, the differences between crops due to crop-specific seedbed preparation mostly do not change. Mulch till has a protective effect mainly during the winter period, which is rather similar for different spring-sown crops and which can be accounted for by reducing the summable C factor of a conventionally-sown row crop by 0.083 (SD 0.015). Table 2 summarizes the equations and rules for estimating the summable C factor of a crop that has not been included in this analysis, or to adjust the specified summable C factors to different conditions.

The summable C factors of specialty crops, which were derived using a simplified approach by applying Eq. (4), were in some cases considerably higher than those of sunflower, WPS maize or soybean (Table 3). In particular, the C factors for onion (fall onions even 0.465) and cucumber (0.365) were extraordinarily high.

3.3. Double cropping

If maize is sown late, the SB period becomes shorter (Fig. 1; see also Fig. A2). It decreased from 40 d to 21 d when sowing was shifted from early April to the end of July. The crop stage P10 % was then also shorter, except for very late sowing dates when it lengthened again due to the decrease in air temperature in September. If maize is sown after 25 June (which would be unusual), the crop stage P75 % is not reached. If sowing takes place after 15 July, not even crop stage P50 % is reached before harvest. If maize is sown during the typical period for double-cropping systems (20 May to 10 June), then maize will reach crop stage P75 %.

During this period, the summable C factor remained almost constant at 0.261 (SD 0.009). The C factors differed slightly only at the very beginning and end of this period (0.264 and 0.276 respectively). The date of the WPS grain harvest therefore does not have to be taken into consideration. The summable C factor of maize in this double-cropping system, including the preceding WPS grain, was 6 % higher than the summable C factor of conventional single crop maize (0.252), in contrast to the hypothesis of lower soil loss under double cropping due to an assumed year-round soil cover (Herrmann, 2013). Compared to direct drill silage maize, the C factor of WPS maize was five times higher. WPS maize therefore cannot be regarded as being environmentally friendly. It cannot compensate for the negative effects caused by the increase in maize cropping following the promotion of biogas for renewable energy in a number of European countries (EEA, 2007; Herrmann, 2013). In contrast, direct drill maize also has other ecological advantages besides soil conservation (see Auerswald et al., 2000) that should be taken into account.

3.4. Regional variation

The differences in crop stage dates between individual observation locations were large. For instance, the 95 % interval of maize sowing within one individual year was 18 d on average when all 60 observation years were taken into account (1149 locations per year on average). This seems to suggest large regional differences in C factors. However, the equations in Table 3 imply that $D_{10\%}$ is a better indicator for γ than the sowing date. The slope between the sowing date and the start of elongation, which is close to $D_{10\%}$ (Auerswald and Menzel, 2021), was only 0.70 and r^2 was 0.2003 (n = 24 666), indicating that 80 % of the variation was random and that the initial difference decreased to 13 d (± 1 week around the mean) and decreased further as crop development proceeded (± 3 d at harvest). Furthermore, the variation in sowing dates was largely due to differences in farm management between individual farms, rather than regional differences.

To account for regional differences, the analysis of the annual reporter data was repeated for both the warmest and the coldest quarter of stations, based on the average temperature during the growing season (March to November; for the spatial distribution of the warmest and the coldest quarters see Fig. A2 in the appendix). Both differed from the mean temperature (11.6 °C) by 1.1 °C, however in opposing directions. The sowing date for row crops differed from the mean date by ± 3 d, and this difference decreased to ± 1 d by the time of harvest. For spring-sown cereals, the variation in sowing dates was larger (± 5 d) and increased to ± 7 d by the time of harvest. In warm regions, fall-sown crops were sown 2 d later and harvested 6 d earlier than average. The differences between crops within these crop groups were negligible.

Overall, there were only small differences in the summable C factors between the warmest 25 % and the coldest 25 % of stations. This was due to the rather small temporal variation in the development of plant soil cover, which decreased further as crop development proceeded. Rotation C factors were only 3.3 % smaller than average ($r^2 = 0.9986$) in the warmest 25 % of stations, whereas in the coldest 25 %, rotation C factors were 3.8 % larger than average ($r^2 = 0.9987$). This effect was only small as the slight variations in crop development cancelled each other out within a crop rotation. Although the dates of crop development often varied, they did so in different directions. For example, on the one hand, faster crop development provides earlier soil protection. On the other hand, earlier harvesting means the susceptible stage after harvesting occurs during a period of higher rain erosivity, which would not be the case if harvesting took place later. Therefore, in most cases the temperature will not need to be taken into consideration. Nevertheless, a deviation in temperature between March and November from the overall mean of 16.6 °C can be taken into account by changing the C factor of a rotation by -3.2 % per centigrade increase.

As there are only minor regional effects within Germany, it can be assumed that the summable C factors will also apply for neighboring countries with similar climate patterns. We show this for the Swiss Plateau (excluding the high elevation areas with different growing conditions), for which detailed information is available (Büchi et al., 2016; Prasuhn, 2012, 2020; Prasuhn and Blaser, 2018). The *REI* distribution is very similar to the German distribution with slightly less erosivity falling during the winter months (e.g. November to February receive 9 % but 12 % in Germany). This difference is probably due to the older Swiss database (from approximately 1980–2000) that does not include the latest increase in winter erosive rains due to climate change. The former German *REI* distribution (data from 1960 to 1980; Rogler and Schwertmann, 1981) showed only 3 % of erosivity occurred during this period, but this increased to 12 % for the period 2001–2017 (Auerswald et al., 2019a).

Crop development taken from Prasuhn and Blaser (2018) is also rather similar to the crop stage dates used here ($r^2 = 0.9755$; RMSE 12 d; without maize 11 d). However, a consistent difference was found for the early stages of maize, which is sown later in Switzerland. This difference is also probably due to climate change and the high sensitivity of maize to warming: in Germany, maize has been sown 3.1 d earlier every 10 years over the last six decades (Auerswald and Menzel, 2021). The Swiss data were collected in 2013/2014 and reflect the preceding decade while our data apply for 2025. Moreover, the *SLR*s in Switzerland are identical to those used here (Prasuhn and Blaser, 2018). Identical C factors must therefore result if the climate-change induced differences in *REI* distribution and maize development are considered. An analogous situation can be expected, at least in regions close to the German border, in the nine countries neighboring Germany (for location of other countries see Fig. A1 in the appendix).

Nevertheless, different socio-economic and environmental conditions in neighboring countries may mean that other land management systems are used, leading to different C factors for rotations, despite similarities in crop development, *REI* distribution and *SLR*s. For example, in Switzerland, sod-based rotations are much more common and not restricted to organic farms like in Germany. Sod-forming crops cover 32 % of arable land in Switzerland (FSO, 2020). In addition, direct drill row crops are more common than in Germany. Both of these differences result in lower C factors in Switzerland (Prasuhn, 2012, 2020) than in Germany, but these differences can be taken into account by using summable C factors.

3.5. Using summable C factors

Summable C factors were negative for sod crops, while C factors of rotations cannot become negative. When calculating the C factor for a given proportion of crops, erroneous negative C factors could result (e.g. if small grain follows the sod crop where the sod effect is smaller than the mean given in Table 1). To avoid this, the summable C factors have to be combined as follows, where 0.025 was the smallest C factor found in 261 rotations:

$$C = \min\left(0.025; \sum_{i=1}^{m} f \times \gamma_i\right) \tag{7}$$

Summable C factors do, however, entail larger uncertainty than a calculation based on detailed information about site-specific crop rotations. This should be borne in mind when using them. As already shown, the uncertainty is especially large for sod-based crop sequences. This is in part due to the confidence intervals, which are larger for sod than for other crops. If the effect of sod-forming crops is to be accurately assessed, information on the type of crop establishment and cultivation, and on the length of use, is required.

A second issue is that even though rotations have almost been abandoned in practice and summable C factors do not require rotations, some of the rules for rotations are still valid. These rules were considered in the calculations and they cannot be ignored when using the summable C factors. This applies especially in cases where a particular preceding crop is required. For example, using the very low summable C factor for a second-year sod is only possible if there was a first-year sod for at least the same number of years or covering the same total area. Analogously, the low values of mulch till or direct drill summable C factors for row crops can only be used if a small-grain crop was grown for the same number of years or with the same total area, as this small-grain crop is necessary so that a cover crop can be established that provides the mulch material. Hence, when modelling various crop rotation options, a 100 % row crop rotation cannot be replaced by a 100 % direct drill rotation but only by a 50 % small grain, 50 % direct drill rotation. Furthermore, it is necessary to know or to define whether the sequence of crops is small grain - row crop - small grain - row crop or whether it is small grain - small grain - row crop - row crop. Despite an identical proportion of small grain and row crops in both cases, only the first scenario means mulch till or direct drill can be used when the row crop is sown, while in the second scenario this would only be possible in the first row crop year.

3.6. Organic farming

We did not specifically analyze organic farming but the major components of typical organic crop rotations, namely sod crops and grain legumes, have been included in our analysis. Compared to the conventional C factors for crop rotations, the summable C factors depict the diverse rotations in organic farming (Barbieri et al., 2017) much more accurately. Other influences are negligible. A comparison of sowing and harvest dates, and also of intermediate crop stages, did not show consistent differences between organic and conventional agriculture. Even if in some cases a crop stage may be delayed in organic farming, e.g. due to lower nutrient supply or due to mechanical weeding (Arnhold et al., 2014), or if a certain level of soil cover is reached earlier due to a larger weed component (Arnhold et al., 2014), these differences would only last for a short period of time and their effect would not be larger than the uncertainty of summable or rotation C factors.

The best (i.e. lowest) C factor for conventional rotations results from a rotation where a small grain crop is followed by a frost-intolerant cover crop, which alternates with direct drill row crops. This results in a rotational C factor of about (0.075 + 0.046)/2 = 0.060 (0.075 is the mean of all fall-sown crops and 0.046 is the mean of all direct drill row crops). Despite their many ecological and economic advantages, these rotations are hardly ever used in Germany (Auerswald et al., 2000), because they require sophisticated crop management to avoid soil compaction. Remarkably, a typical rotation in organic farming may comprise two years of sod, one year of a row crop, one year of a cereal and one year of a grain legume. This results in a rotational C factor of about 0.05 if the sod is established by undersowing. This would, even without specifically aiming to create a crop rotation focusing on soil protection, be better than the best conventional rotation. The lower soil loss in organic farming, which has been reported in several studies (Reganold et al., 1987; Auerswald et al., 2018), is mainly due to the integration of sods in crop rotations. Sods, however, are not exclusively restricted to organic farming but can also be used in conventional farming, as is often the case in Switzerland. In particular, farms that produce biogas could easily integrate sods into their rotations.

Our approach does not consider any inherent difference between conventional and organic farming systems other than crop rotation. There is currently insufficient generalizable evidence on whether organic agriculture has an influence on the susceptibility to erosion that is not due to crop rotation design and already included in the summable C factors. For example, higher aggregate stability or earthworm abundance caused by sods are already considered in the carry over effect and should not be taken into account twice.

3.7. Application to cropping statistics

In Germany, 116 095 km^2 are covered by crops in rotations, according to official county statistics (www.destatis.de). For 4.5 % of this area, the crop class was not specific enough (e.g. ornamental flowers, miscellaneous crops) and therefore γ could not be determined. No γ was available for tobacco, which made up 0.02 % of the total crop area. Gammas were available for the remaining 95.5 %, comprising 23 crop classes (Table 4). In one case (mixed spring-sown small grain; 0.09 %) the average for all spring-sown small grains was used. Hence, there were enough γ available to calculate a national C factor. However, 17 out of the 34 gammas given in Table 1 were not used because insufficient information was available from cropping statistics. This was especially true for mulch till and direct drill crops. Hence, conventional tillage had to be assumed in all cases because of insufficient information, which means that the national C factor is probably a (small) overestimation (see below). From Table 3 only 1 out of 23 γ could be used because cropping statistics were not detailed enough in the case of specialty crops. When combining the fraction of land and the γ of all 23 crop classes, the mean national C factor was then 0.124 (Table 4). Silage maize contributed the largest share to the mean C factor (39 %), followed by fall wheat (19 %), while all other crops contributed less than 10 %. As a result, the largest reduction in total soil loss can be achieved by cultivation techniques that lower the γ of these two crops.

The national C factor has several advantages. It makes it easy to see whether a farmer, a county or a region is better or worse than the German average. Furthermore, in order to characterize the site-specific erosion potential without including how the soil or land is used, often the soil loss under long-term seedbed conditions (C = 1.0) is calculated (e.g. Plambeck, 2020). This leads to unrealistically high soil loss rates. These rates do not directly show those areas where action should be taken. Maps using the national C factor show more realistic soil loss rates. More importantly, these maps then immediately show those areas where average arable soil use causes high soil losses above a certain threshold (e.g. 10 t ha^{-1} a^{-1}) and where better soil protection measures are required.

Official county statistics do not include the type of tillage used. However, the INVEKOS database (INtegriertes VErwaltungs- und KOntrollSystem zur Kontrolle von flächengestützten Förderanträgen; integrated administration and control system for European Community aid schemes), which is used to administer the payment of agricultural subsidies, does partly include this information, if the particular type of tillage is subsidized. It also contains much more detailed information regarding the crop types. INVEKOS, however, differs between German states because subsidy schemes differ between the states. As an example, we used the INVEKOS statistics from Bavaria (not published; confidential), which lists a total of 164 crops in rotations, grown on 19 573 km^2. Without taking the sowing system into account, γ was available for 72 crops, which covered 99.4 % of the total area (i.e., the remaining 92 crops covered only 0.6 % of the total area). Most crops for which no γ was available were either ornamental plants, (medicinal) herbs or groups of undifferentiated crops (e.g. "other vegetables"). Of the crops for which no γ was available, spring canola made up the largest areal share (0.03 %). The area-weighted C factor was 0.132. If sod crops were excluded, the average was 0.148.

The INVEKOS database differentiates between conventional till (98.2 %), mulch tillage (1.7 %) and direct drill (0.08 %). The loss of management information in the Destatis database is thus rather minor. We combined mulch tillage and direct drill because of the low percentage of direct drill and because a study had shown that fields listed as direct drill in this database did not actually have the required amount of mulch cover (Auerswald et al., 2018). Mulch till was used in a total of 17 crops, with grain maize (44 %), silage maize (42 %) and sugar beet (4 %) making up the largest proportion. All other crops contributed only 0.2 %. For four crops a γ was available from Table 1, while for nine other crops γ could be calculated based on Table 2. For four crops no γ could be assigned because the γ for conventional till was missing. The area-weighted mean C factor was 0.157 while it would have been 0.242 for the same crops and conventional till, indicating a mean reduction in erosion by 35 % due to the use of mulch till or direct drill. However, despite subsidies, these tillage types are used on only 1.8 % of the land cultivated using rotational cropping systems. The overall effect of this conservation tillage is thus small.

4. Conclusions

Summable C factors facilitate the calculation of rotational C factors when only the share of crops but not the sequence of crops is known. Thus, they are particularly helpful for regional studies, land-use planning and designing subsidy schemes where exact rotations and the timing of agricultural operations are not known.

Both the summable C factors and the C factors for rotations showed only a small regional variation; this was particularly the case for the rotation C factors. Although there was considerable variation in the timing of agricultural operations and crop development, most differences cancelled each other out within and between crops. Thus, the summable C factors derived here can be applied throughout Germany and in neighboring countries.

Among the common arable crops, potatoes have the largest summable C factor, while sod-forming crops can even have negative values, resulting in low C factors for crop rotations. The low soil loss of organic farms and in Switzerland is mainly due to the great importance of sod crops in organic rotations and crop cultivation in Switzerland.

The influence of climate change on the seasonal distribution of rainfall erosivity and on crop development caused a narrowing of the range of C factors. C factors of crops with low erosion potential (small grain) increased, while those of crops with high erosion potential (row crops) decreased.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

Crop stage development under various conditions found in agricultural practice and the range of management options applied by farmers were discussed with a large number of experts who also contributed data. We would like to mention in particular Dr. Jörn Breuer, Dr. Xaver Maidl, Dr. Hans-Jürgen Reents, Dr. Norbert Röder, Dr. Peter Strauss, Dr. Klaus Wiesinger and Dr. Peer Urbatzka.

Appendix

Example of the C factor calculation and the determination of gamma:

An example of how to derive the C factor according to the USLE is given in Table A3 for the most common crop rotation consisting of conventionally sown silage maize followed by fall wheat and fall barley. Further C factors for six other rotations with the same crops, including the option where the maize is directly drilled into mulch cover instead of conventionally sown, are given in Table A4. Table A4 also shows the dependent and independent variables for the multiple regression. The resulting multiple regression was:

$$y = 0.254 \times x_1 + 0.060 \times x_2 + 0.079 \times x_3 + 0.065 \times x_4.$$

The coefficient of determination was 0.99995 and the slopes of variables x_1 to x_4 were the desired gammas. These slopes differ to some degree from the gammas reported in Table 1 given the small subset and the large flexibility of the multiple regression with a sample size of only six but with four explanatory variables. Despite the apparent deviation, the gammas in Table 1 predict the mean annual C factors of the rotations in Table A4 well. The RMSE was only 0.002 while the mean annual C factors varied between 0.067 and 0.254.

References

Arnhold, S., Lindner, S., Lee, B., Martin, E., Kettering, J., Nguyen, T.T., Koellner, T., Ok, Y.S., Huwe, B., 2014. Conventional and organic farming: Soil erosion and conservation potential for row crop cultivation. Geoderma 219-220, 89–105. https://doi.org/10.1016/j.geoderma.2013.12.023.

Auerswald, K., 1985a. Beurteilung der Erosionsanfälligkeit von Mais bei unterschiedlichen Anbauverfahren. J. Agronomy Crop Sci. 154, 45–55.

Auerswald, K., 1985b. Erosionsgefährdung unter Zuckerrüben und Sommergerste. J. Agronomy Crop Sci. 155, 34–42.

Auerswald, K., Kainz, M., 1998. Erosionsgefährdung durch Sonderkulturen (C-Faktor). Bodenschutz 3, 98–102.

Auerswald, K., Menzel, A., 2021. Change in erosion potential of crops due to climate change. Agricultural Forest Meteorol. 300, 108338 https://doi.org/10.1016/j.agrformet.2021.108338.

Auerswald, K., Albrecht, H., Kainz, M., Pfadenhauer, J., 2000. Principles of sustainable landuse systems developed and evaluated by the Munich Research Alliance on Agroecosystems (FAM). Petermanns Geogr. Mitt. 144, 16–25.

Auerswald, K., Fischer, F.K., Kistler, M., Treisch, M., Maier, H., Brandhuber, R., 2018. Behavior of farmers in regard to erosion by water as reflected by their farming practices. Sci. Total Environ. 613–614, 1–9. https://doi.org/10.1016/j.scitotenv.2017.09.003.

Auerswald, K., Fischer, F.K., Winterrath, T., Brandhuber, R., 2019a. Rain erosivity map for Germany derived from contiguous radar rain data. Hydrol. Earth Syst. Sci. 23, 1819–1832. https://doi.org/10.5194/hess-23-1819-2019.

Auerswald, K., Fischer, F., Winterrath, T., Elhaus, D., Maier, H., Brandhuber, R., 2019b. Klimabedingte Veränderung der Regenerosivität seit 1960 und Konsequenzen für Bodenabtragsschätzungen. In: Bachmann, G., König, W., Utermann, J. (Eds.), Bodenschutz, Ergänzbares Handbuch der Maßnahmen und Empfehlungen für Schutz, Pflege und Sanierung von Böden, Landschaft und Grundwasser (Loseblattsammlung), 4090. Erich Schmidt Verlag, Berlin, 21. p.

Barbieri, P., Pellerin, S., Nesme, T., 2017. Comparing crop rotations between organic and conventional farming. Sci. Rep. 7, 13761. https://doi.org/10.1038/s41598-017-14271-6.

Büchi, L., Valsangiacomo, A., Burel, E., Charles, R., 2016. Integrating simulation data from a crop model in the development of an agri-environmental indicator for soil cover in Switzerland. Eur. J. Agron. 76, 149–159. https://doi.org/10.1016/j.eja.2015.11.004.

Cebecauer, T., Hofierka, J., 2008. The consequences of land-cover changes on soil erosion distribution in Slovakia. Geomorphol. 98, 187–198. https://doi.org/10.1016/j.geomorph.2006.12.035.

Chochois, V., Vogel, J.P., Rebetzke, G.J., Watt, M., 2015. Variation in adult plant phenotypes and partitioning among seed and stem-borne roots across *Brachypodium distachyon* accessions to exploit in breeding cereals for well-watered and drought environments. Plant Physiol. 168, 953–967. https://doi.org/10.1104/pp.15.00095.

Chow, T.L., Rees, H.W., 1994. Effects of potato hilling on water runoff and soil erosion under simulated rainfall. Can. J. Soil Sci. 74, 453–460.

Destatis, 2020. Anbauflächen, Hektarerträge und Erntemengen ausgewählter Anbaukulturen im Zeitvergleich. Deutsches Statistisches Bundesamt (last access: 30.06.2020). https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Feldfruechte-Gruenland/Tabellen/liste-feldfruechte-zeitreihe.html.

DIN – Deutsches Institut für Normung, 2017. DIN 19708:2017-08 Bodenbeschaffenheit – Ermittlung der Erosionsgefährdung von Böden durch Wasser mit Hilfe der ABAG. Beuth, Berlin, Deutschland.

Dose, V., Menzel, A., 2004. Bayesian analysis of climate change impacts in phenology. Global Change Biol. 10, 259–272. https://doi.org/10.1111/j.1529-8817.2003.00731.x.

DWD, 2014. Anleitung für die phänologischen Beobachter des Deutschen Wetterdienstes. Vorschriften und Betriebsunterlagen Nr. 17, 177 p., last access 26 Oct. 2020. Deutscher Wetterdienst, Offenbach.. https://www.dwd.de/DE/klimaumwelt/klimaueberwachung/phaenologie/daten_deutschland/beobachtersuche/beobachteranleitung.html

DWD, 2021. Historical Daily Station Observations (temperature, Pressure, Precipitation, Sunshineduration, etc.) for Germany (last access: 14 June 2021). https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/historical/.

Edwards, C.A., Bohlen, P.J., 1996. Biology and Ecology of Earthworms, 3rd ed. Chapman & Hall, London, UK.

EEA, 2007. Estimating the Environmentally Compatible Bioenergy Potential from Agriculture. European Environment Agency Technical Report no.12/2007.

Estrella, N., Sparks, T., Menzel, A., 2007. Trends and temperature response in the phenology of crops in Germany. Global Change Biol. 13, 1737–1747. https://doi.org/10.1111/j.1365-2486.2007.01374.x).

Evans, R., Collins, A.L., Foster, I.D.L., Rickson, R.J., Anthony, S.G., Brewer, T., Deeks, L., Newell-Price, J.P., Truckell, I.G., Zhang, Y., 2016. Extent, frequency and rate of water erosion of arable land in Britain - benefits and challenges for modelling. Soil Use Manag. 32, 149–161.

Fiener, P., Auerswald, K., 2007. Rotation effects of potato, maize and winter wheat on water erosion. Soil Sci. Soc. Am. J. 71, 1919–1925. https://doi.org/10.2136/sssaj2006.0355.

Fiener, P., Neuhaus, P., Botschek, J., 2013. Long-term trends in rainfall erosivity–analysis of high resolution precipitation time series (1937–2007) from Western Germany. Agricultural Forest Meteorol. 171–172, 115–123.

Folly, A., Bronsveld, M.C., Clavaux, M., 1996. A knowledge-based approach for C-factor mapping in Spain using Landsat TM and GIS. Int. J. Remote Sens. 17 (12), 2401–2415. https://doi.org/10.1080/01431169608948780.

Foster, G.R., 2008. Draft: Science Documentation. Revised Universal Soil Loss Equation Version 2 (RUSLE2). USDA-Agricultural Research Service, Washington, D.C (last access 15 June 2021). https://fargo.nserl.purdue.edu/rusle2_dataweb/userguide/RUSLE2_User_Ref_Guide_2008.pdf.

FSO, 2020. Employees, Farmholdings, Utilized Agricultural Area and Livestock on Level 2 of Classification by Canton. Swiss Federal Statistical Office (FSO) (last access 15 June 2021). https://www.bfs.admin.ch/bfs/en/home/statistics/agriculture-forestry.assetdetail.16984928.html.

Graß, R., Heuser, F., Stülpnagel, R., Piepho, H.-P., Wachendorf, M., 2013. Energy crop production in double-cropping systems: results from an experiment at seven sites. Eur. J. Agron. 51, 120–129.

Herrmann, A., 2013. Biogas production from maize: current state, challenges and prospects. 2. Agronomic and environmental aspects. Bioenerg. Res. 6, 372–387. https://doi.org/10.1007/s12155-012-9227-x.

Hirl, R., Schnyder, H., Ostler, U., Schäufele, R., Schleip, I., Vetter, S., Auerswald, K., Baca Cabrera, J., Wingate, L., Barbour, M., Ogée, J., 2019. The ^{18}O ecohydrology of a grassland ecosystem – predictions and observations. Hydrol. Earth Syst. Sci. 23, 2581–2600. https://doi.org/10.5194/hess-23-2581-2019.

Jenkins, T., 2020. Pasture management to boost organic matter. OrganicNZ 79 (4), 44–45.

Kainz, M., 1989. Runoff, erosion and sugar beet yields in conventional and mulched cultivation. Soil Technol. Ser. 1, 103–114.

Kaspar, F., Zimmermann, K., Polte-Rudolf, C., 2014. An overview of the phenological observation network and the phenological database of Germany's national meteorological service (Deutscher Wetterdienst). Adv. Sci. Res. 11, 93–99. https://doi.org/10.5194/asr-11-93-2014.

Kohavi, R., 1995. A study of cross-validation and bootstrap for accuracy estimation and model selection. Proc. 14th Int. Joint Conf. Artificial Intelligence 338–345.

Leteinturier, B., Herman, J.L., Longueville, F.D., Quintin, L., Oger, R., 2006. Adaptation of a crop sequence indicator based on a land parcel management system. Agric. Ecosyst. Environ. 112, 324–334. https://doi.org/10.1016/j.agee.2005.07.011.

Matthew, C., van Loo, E.N., Thom, E.R., Dawson, L.A., Care, D.A., 2001. Understanding shoot and root development. Proc. XIX Int. Grassland Congr. 19–26.

Menzel, A., von Vopelius, J., Estrella, N., Schleip, C., Dose, V., 2006. Farmers' annual activities are not tracking the speed of climate change. Climate Res. 32 (3), 201–207. https://doi.org/10.3354/cr032201.

Menzel, A., Yuan, Y., Matiu, M., Sparks, T., Scheifinger, H., Gehrig, R., Estrella, N., 2020. Climate change fingerprints in recent European plant phenology. Global Change Biol. 26, 2599–2612. https://doi.org/10.1111/gcb.15000.

Pena-Yewtukhiw, E.M., Romano, E.L., Waterland, N.L., Grove, J.H., 2017. Soil health indicators during transition from row crops to grass–legume sod. Soil Sci. Soc. Am. J. 81, 1486–1495. https://doi.org/10.2136/sssaj2016.12.0439.

Plambeck, N.O., 2020. 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. Ecol. Indicators 118, 106732. https://doi.org/10.1016/j.ecolind.2020.106732.

Prasuhn, V., 2012. On-farm effects of tillage and crops on soil erosion measured over 10 years in Switzerland. Soil Tillage Res. 120, 137–146. https://doi.org/10.1016/j.still.2012.01.002.

Prasuhn, V., 2020. Twenty years of soil erosion on-farm measurement: annual variation, spatial distribution and the impact of conservation programmes for soil loss rates in Switzerland. Earth Surf. Process. Landforms 45, 1539–1554.

Prasuhn, V., Blaser, S., 2018. Der Agrarumweltindikator «Erosionsrisiko». Bulletin BGS 39, 11–18.

R Core Team, 2019. R—A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reganold, J.P., Elliott, L.F., Unger, Y.L., 1987. Long-term effects of organic and conventional farming on soil erosion. Nature 330 (6146), 370–372. https://doi.org/10.1038/330370a0.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting Soil Erosion by Water: a Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook 703. U.S. Department of Agriculture, Washington, DC.

Rogler, H., Schwertmann, U., 1981. Erosivität der Niederschläge und Isoerodentkarte Bayerns. Zeitschrift für Kulturtechnik und Flurbereinigung 22, 99–112.

Schwertmann, U., Vogl, W., Kainz, M., 1990. Bodenerosion durch Wasser: Vorhersage des Abtrags und Bewertung von Gegenmaßnahmen, 2. ed. Ulmer, Stuttgart, Germany.

Stein, S., Steinmann, H.-H., 2018. Identifying crop rotation practice by the typification of crop sequence patterns for arable farming systems – a case study from Central Europe. Eur. J. Agron. 92, 30–40.

Steinhoff-Knopp, B., Burkhard, B., 2018. Soil erosion by water in Northern Germany: long-term monitoring results from Lower Saxony. Catena 165, 299–309.

Tariq, M., Ali, H., Hussain, N., Nasim, W., Mubeen, M., Ahmad, S., Hasanuzzaman, M., 2019. Fundamentals of crop rotation in agronomic management. In: Hasanuzzaman, M. (Ed.), Agronomic Crops: Vol. 1: Production Technologies. Springer, Singapore, pp. 545–559.

Waldhoff, G., Lussem, U., Bareth, G., 2017. Multi-data approach for remote sensing-based regional crop rotation mapping: a case study for the Rur catchment, Germany. Int. J. Appl. Earth Obs. Geoinf. 61, 55–69. https://doi.org/10.1016/j.jag.2017.04.009.

Wischmeier, W.H., 1960. Cropping-management factor evaluations for a universal soil-loss equation. Soil Sci. Soc. Am. Proc. 24, 322–326.

Wischmeier, W.H., Smith, D.D., 1965. Predicting Rainfall Erosion Losses From Cropland East of the Rocky Mountains: a Guide for Selection of Practices for Soil and Water Conservation. Agricultural Handbook, No. 282, 47 p..

Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Agriculture Handbook, Issue 537. US Department of Agriculture, Washington, DC.

Yang, J.Z., Matthew, C., Rowland, R.E., 1998. Tiller axis observations for perennial ryegrass (*Lolium perenne*) and tall fescue (*Festuca arundinacea*): number of active phytomers, probability of tiller appearance, and frequency of root appearance per phytomer for three cutting heights. New Zealand J. Agric. Res. 41, 11–17.