Soil & Tillage Research 215 (2022) 105199

Contents lists available at ScienceDirect

Soil & Tillage Research

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

# Experience with the assessment of the USLE cover-management factor for arable land compared with long-term measured soil loss in the Swiss Plateau

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ARTICLE INFO

*Keywords:*
C-factor
Soil loss
USLE
Long-term measurement
Conservation tillage

ABSTRACT

The cover-management factor (C-factor) of the Universal Soil Loss Equation (USLE) is the most important factor for estimating the effects of farming practices or agricultural policy measures on soil loss rates. This study, conducted in Switzerland from 1987 to 2017, assessed the impact of mitigation measures on arable land by comparing modelled C-factor values and measured soil losses. C-factor values were calculated in detail for 203 fields for five different periods (1987–89, 1997–99, 1997–2006, 2003–09, 2010–14) using a C-factor tool adapted to Swiss conditions. The C-factor values were compared with the measured soil loss rates of the same fields from the three periods 1987–89, 1997/98–2006/07, and 2007/08–2016/17. Given various action programmes, the share of conservation tillage practices increased from 4% in 1997/98 to 85% in 2014/15. The mean annual soil loss was 0.71 t $ha^{-1}$ $yr^{-1}$ (1987–89) and decreased by over two-thirds from 0.74 t $ha^{-1}$ $yr^{-1}$ (1997/98–2006/07) to 0.20 t $ha^{-1}$ $yr^{-1}$ (2007/08–2016/17), while the mean C-factor values were 0.136 in 1987–89 and decreased by almost half from 0.094 (1997–99) to 0.050 (2010–14). This study demonstrates that, with an in-depth calculation of C-factor values over different periods, changes amounting to soil loss resulting from the implementation of mitigation measures can be satisfactorily reproduced for a region.

## 1. Introduction

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its derivatives, such as the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), remain the most widespread erosion models worldwide despite various weaknesses and shortcomings (Laflen and Moldenhauer, 2003; Alewell et al., 2019; Fiener et al., 2020). Among the USLE factors, the cover-management factor (C-factor) is perhaps the most important factor regarding the sensitivity of the computed soil loss (Foster, 1982) and the key factor in soil erosion control (Pierce et al., 1986; Schönbrodt et al., 2010; Zhao et al., 2013). Rainfall erosivity (R-factor), soil erodibility (K-factor), and the topographic factors slope steepness and slope length (LS-factors) of the USLE are relatively static factors, which hardly change at a certain location in the short term and can hardly be influenced by the farmer. They are nature dependent or intrinsic to the landscape and independent from anthropogenic interventions (Nyakatawa et al., 2001). Changes in mean annual R-factor occur in the long-term from climate change-induced modifications in rainfall amount or the number and intensity of heavy rainfall events (Mullan, 2013). For the K-factor, the grain size distribution is usually stable over time. In the medium to long term, aggregate stability and water permeability can be changed by land use and soil management (e.g. humus supply or humus depletion, liming) (Bryan, 2000). With the LS-factor, the erosive slope length can be changed by melioration (change of field size, removal, or creation of barriers such as hedges and buffer strips) (Van Oost et al., 2000). Conversely, the C-factor and the support practice factor (P-factor) are dynamic factors of the USLE and can be strongly influenced in the short term by the farmer and by agricultural policy or financial incentive programmes. Therefore, a detailed assessment of the C-factor is imperative, as this factor should reflect changes in agricultural practices (best management practices). However, determining the C-factor accurately and adequately for use in soil erosion modelling is time-intensive.

There are numerous studies on individual USLE factors: R-factor (Meusburger et al., 2012; Nearing et al., 2017), K-factor (Auerswald et al., 2014; Preetha and Al-Hamdan, 2019), and LS-factor (Kinnell, 2001; Zhang et al., 2017; Bircher et al., 2019). In USLE-based assessments, these three factors are generally recorded in detail (Benavidez et al., 2018; Alewell et al., 2019), while for the C- and P-factor values from literature are often used. However, there are comparatively few

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https://doi.org/10.1016/j.still.2021.105199
Received 3 May 2021; Received in revised form 22 July 2021; Accepted 27 August 2021
Available online 28 September 2021
0167-1987/

studies on the C- and P-factors, especially for arable land. Nevertheless, arable land is mostly affected by erosion in many regions. Therefore, it is essential to determine the C-factor as accurate and robust as possible. An alteration of the support practice factor (P) in practice (e.g. contour farming, terracing) often requires considerable monetary costs (Panagos et al., 2015). Hence, in practice, the C-factor can be managed with less effort and cost to reduce soil losses at the field level (Nyakatawa et al., 2001).

The C-factor refers to the soil loss ratio (SLR) under actual specific crop conditions of a particular crop's phenological period (for arable land) or plant development stage (for grassland) to the corresponding soil loss from clean-tilled, continuous bare fallow under standard conditions weighted by its corresponding fraction of the R-factor (Wischmeier and Smith, 1978). The C-factor is defined as a non-dimensional number and ranges between zero (very high crop cover protecting the topsoil from soil erosion) and one (no crop cover and high soil loss). For specific land uses other than arable land or grassland, separate methods for determining C-factors have been developed for forest (Dissmeyer and Foster, 1981), rangeland (Foster, 1982), and the special conditions of mining, construction, and reclamation lands (Toy et al., 1999).

Alternatively, following the RUSLE handbook (Renard et al., 1997), SLRs are a product of multiplication of five sub-factors (prior land use, canopy cover, surface cover, surface roughness, and soil moisture). Afterwards, a weighted average is calculated for the corresponding period and multiplied by the corresponding percentage of annual R-factor. However, assessing each of these sub-factors to calculate the given SLR is time-intensive (Schönbrodt et al., 2010). Therefore, simplified approaches to calculating the C-factor are often used.

For C-factor calculations, values are usually collected for different land use categories such as grassland, forest, arable land, and vineyards for entire catchment areas, regions, or countries (Chen et al., 2011; Zhang et al., 2011; Zhao et al., 2013). To determine the spatial and temporal distribution of C-factors, satellite-based methods, remote-sensing techniques, and image classification are most commonly used to identify the different land uses and land cover classes as a function of ground cover (Wang et al., 2002; Vrieling, 2006; Zhang et al., 2011). In the beginning, Landsat images were used (De Jong, 1994) later, the CORINE Land Cover database combining remote sensing and census information was widely adopted for C-factor derivation on a European scale (van der Knijff et al., 2000). Presently, various remote-sensing methods and techniques using satellite data have been proposed. Bargiel et al. (2013) used high resolution radar images acquired by the TerraSAR-X satellite in south-eastern Poland; Kouli et al. (2009), Chen et al. (2011), and Almagro et al. (2019) used normalised difference vegetation index (NDVI) derived from Landsat in Greece, China, and Central-West Brazil, respectively. Meusburger et al. (2010) created detailed land-cover and fractional vegetation cover (FVC) maps using linear spectral unmixing and supervised classification of QuickBird imagery in an alpine catchment in Switzerland; Schönbrodt et al. (2010) derived the FVC based on Landsat-TM images in Central China and Yang (2014) in New South Wales and Australia. Schmidt et al. (2018) used the fraction FVC to determine the SLRs for grasslands to result in spatio-temporal C-factors for Swiss grasslands. Schmidt et al. (2018) and Alexandridis et al. (2015) mentioned that due to the phenology of the plants, the effects of seasonality must be considered when determining C-factors with remote-sensing data. For arable land, such methods are not yet well established since in addition to soil cover, land management and tillage practices play an important role in determining the C-factor at early growth stages. However, different tillage practices are difficult to derive from remote-sensing data despite progress being achieved (Möller et al., 2017). Nevertheless, remote- and satellite-based sensing in particular may support land use classification and monitoring of FVC temporal and spatial dynamics, supporting higher accuracy of C-factors used in future erosion models.

Detailed studies on the C-factors of arable land are rare (Gabriels et al., 2003). Since spatial data on crop rotation, tillage practices, and cover crops are hardly available (Lorenz et al., 2013), interviews with farmers or detailed field assessments are necessary. For regionally adapted values for the SLRs of different crops, extensive and expensive experiments are necessary (Pierce et al., 1986). Detailed SLRs or C-factor values are rarely reported outside the United States and Germany. Therefore, most of the values used in other studies (e.g. Guo et al., 2015, Almagro et al., 2019) are taken from literature, such as Wischmeier and Smith (1978) or Renard et al. (1997) for the United States and Schwertmann et al. (1990) for Germany. Panagos et al. (2015), for example, used C-factor values for 16 crop types, based on a literature review, to link them to statistical data on agricultural crops for the European Union. The use of C-factors from the published literature of other countries from other geographical regions with different climatic conditions results in some uncertainty on the results (Tanyaş et al., 2015). C-factors should also always be calculated for crop rotations or crop sequences since preceding and succeeding crops can strongly influence the C-values of individual crops (Wischmeier and Smith, 1978).

A detailed assessment of the C-factor is also important for implementing agricultural policy measures (Kelsey and Johnson, 2003; Lorenz et al., 2013; Panagos et al., 2015). The C-factor and its associated soil loss rates can potentially be influenced by land-use changes, crop rotation, and management practices, such as conservation tillage or cover crops. Land-use change (e.g. conversion of arable land to grassland or forest) has the highest impact on the C-factor (Maetens et al., 2012). The impact of mitigation measures, such as cover crops, conservation tillage, organic farming, and crop rotation, can be evaluated (Kelsey and Johnson, 2003; Arnhold et al., 2014; Biddoccu et al., 2016). However, it is important to use recent data because plant breeding and climate change have shifted the phenological development of the crops. The seasonal distribution of erosive rainfall has altered; new management techniques, such as various micro-dam techniques in potato cultivation, new strip-till and reduced tillage practices or organic farming have been developed, and new crop combinations or new intercropping types with different carry-over effects are in use.

C-factors are often used for scenario calculations or evaluations of agricultural policy measures without verifying their effects on real measured soil loss rates. The main objective of this study is to estimate as detailed as possible C-factors for 203 arable fields in Switzerland over five different periods between 1987 and 2014. These C-factors are compared with measured soil loss on the same 203 fields between 1987–1989 and 1997–2017. Finally, the results are discussed regarding agricultural policy measures during this period to estimate the impact of management practices, such as conservation tillage, cover crops, and plant residues, to reduce soil loss rates.

## 2. Methods

### *2.1. Study area*

The study area is located at about 20 km northwest of the city of Bern in the Swiss Plateau. The region falls within the moderate climate zone, with an annual average temperature of 8.5 °C and annual precipitation ranging from 1035 to 1150 mm. The area originally covered a total of 259 fields, with 276 ha of arable land in 1987–89. Until 1997/98, 11 ha of this area were converted into permanent grassland, and 56 fields were merged. In this study, the land use data from 1997/98 were used as a reference (265 ha comprising 203 arable fields with an average size of 1.8 ha) for evaluating the C-factors of all periods investigated and the soil erosion measurements from 1997/98–2016/17.

According to the survey of the farmers, mixed farming with crop production and animal husbandry is predominantly practised by family-run farms having an utilised agricultural area of 17 ha on average. The crop rotation on a given arable field comprises at least four different crops. One of them is most often temporary grassland (mixture of *Lolium multiflorum* and *Lolium perenne, Dactylis glomerata, Trifolium pratense, Trifolium repens,* and others), which is grown for one to three years. The cultivation of cover crops is widespread. Mean slopes of individual fields vary from 0% to 25%, and slope directions change frequently within the field. Most soils are permeable Cambisols and Luvisols over glacial moraine or gravel, predominantly sandy-loamy to clayey-loamy soils, which have been rated to have moderate erodibility. From 1987–1989 and from 1997 to the present, erosion studies have been conducted in this area (Mosimann et al., 1990; Prasuhn, 2020).

In 1999, in Switzerland the Proof of Ecological Performance (PEP) was established, which includes appropriate crop rotation and adequate soil protection measures. Besides the national system of direct payments, there are various cantonal subsidy programmes for conservation tillage. A detailed description of the study area was given in Mosimann et al. (1990), Prasuhn and Grünig (2001), and Prasuhn (2011).

### 2.2. C-factor calculation

The C-factor assessment follows the original approach of Wischmeier and Smith (1978). The C-factor essentially quantifies the interaction of seasonal variation of soil cover with the seasonal variation in the R-factor, averaged over a crop rotation or crop sequence. To calculate the C-factor, the values of the SLR and the regional crop stage periods of the different crops and the regional distribution of the annual erosivity are required. Mosimann and Rüttimann (2006a) have developed a method adapted to Swiss conditions based on the specifications of Wischmeier and Smith (1978) and Schwertmann et al. (1990). This procedure is available as a software tool for the automated calculation of the C-factor for a crop rotation or crop sequence (Mosimann and Rüttimann, 2006b). The required input data are the crop sequence, tillage practices of a given crop, the inter-cropping period (fallow, cover crop, stubble mulch, etc.), and the sowing date and tillage method of the particular cover crop.

The SLR values of the different crops for the crop stage periods were taken from the Mosimann and Rüttimann's (2006a) study. For crops with no values available in the literature, values were determined by analogy to similar crops. Each of these SLR values was weighted by the fraction of the R-factor associated with the corresponding period of the crop stage. The USLE approach divides the growing season into six crop stage periods. For 34 main crops, the timetable for crop stage periods for the Swiss Plateau was determined by Mosimann and Rüttimann (2006a).

- From initial tillage operation to final seedbed preparation.
- From seedbed to 10% soil cover.
- From 10% to 50% soil cover.
- From 50% to 75% soil cover.
- From 75% soil cover to harvest.
- From harvest to ploughing or sowing of the successive crop.

For the last crop stage period, seven options with corresponding SLR values were considered:

- A: Seed of the subsequent main crop within a few days.
- B: Ploughing and bare fallow over autumn and winter.
- C: Stubble fallow in winter.
- D: Stubble fallow until sowing of a winter main crop.
- E: Cover crop in autumn followed by fallow land in winter.
- F: Cover crop in winter, winter-killed.
- G: Cover crop in winter, winter-hardy.

Furthermore, four different tillage practices can be selected for each main crop and each cover crop. A minimum threshold value of 30% soil cover is generally recommended to achieve sufficient erosion control (Zuazo and Pleguezuelo, 2008; Prasuhn, 2012). For each tillage practice, separate SLR values were applied:

- Conventional tillage with mouldboard plough or ploughless tillage with $< 10\%$ soil cover
- Reduced tillage with 10–30% soil cover
- Mulch seeding with $> 30\%$ soil cover
- No-till or strip-till

The SLR values were refined by carry-over effects based on Wischmeier and Smith (1978) and Schwertmann et al. (1990). Three different carry-over effects are automatically considered in the C-factor calculation (Mosimann and Rüttimann, 2006a):

- SLR increases if the leaf crop rate in the crop sequence is $> 50\%$
- SLR increases for cereals and oilseed rape (Brassica napus L.) after root crops
- SLR reduces for succeeding crops in the first and second years after one or more years of temporary grassland

Additionally, the long-term average erosivity of rainfall is included in the calculation of the C-factors. From the 10-min precipitation data of various meteorological stations in the Swiss Plateau over a period of 20 years, the mean erosivity of the rainfall over the year was determined and presented as a cumulative percentage curve (Mosimann and Rüttimann, 2006a). For the duration of each crop stage period of each crop, the corresponding percentage of annual erosivity was determined and calculated with the respective SLR value.

For each of the 203 fields, detailed C-factors were calculated for five periods, and data were obtained from different sources:

1. 1987–1989: Interviews with farmers (Mosimann et al., 1990)
2. 1997–1999: Interviews with farmers (Prasuhn and Grünig, 2001)
3. 1997–2006: Field assessments (Prasuhn, 2012)
4. 2003–2009: Interviews with farmers (Wiggenhauser and Chervet, 2010)
5. 2010–2014: Interviews with farmers (Lazzini, 2016)

The individual periods are of different lengths, the intervals between the periods differ, and the periods overlap partially due to unavailability of data.

### 2.3. Erosion damage mapping

The soil loss was recorded with erosion damage mapping using the method described by Rohr et al. (1990) and DVWK (1996). Erosion damage mapping is an event- and field-based approach and surveys took place on all 203 fields after every erosive precipitation or snow melting

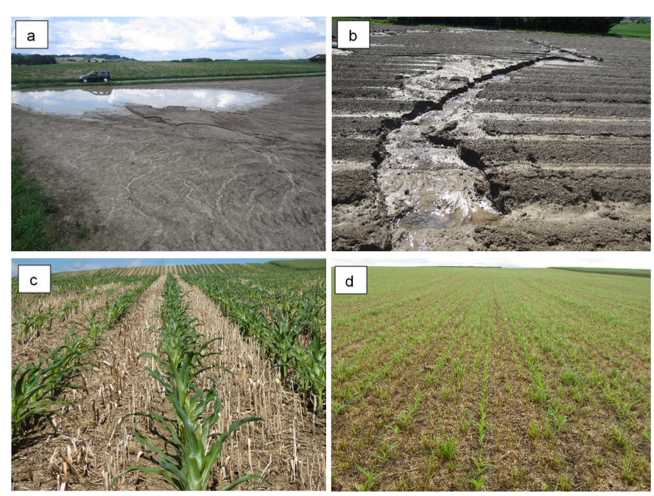


**Fig. 1.** a) Sheet erosion on recently planted vegetables (June 01, 2018), b) rill erosion in recently cultivated potatoes (May 07, 2015), c) no-tillage cropped maize in cover crops (June 07, 2017), d) no-tillage cropped maize in temporary grassland (June 15, 2016).

event. With all linear erosion forms deeper than 2 cm (Fig. 1b) the incision of the rills were measured with a folding ruler and quantified by calculating the volume of soil eroded based on representative cross-sectional areas (mean depth, mean width) and its length. The weight of the eroded soil was determined by multiplying the volume of the eroded soil by the bulk density of the topsoil (1.20 Mg $m^{-3}$ for large rills > 10 cm depth, rills in wheel tracks and furrows; 1.00 Mg $m^{-3}$ for shallow rills after seed bed preparation or sowing, when the topsoil was loosely packed). Soil loss by sheet erosion (Fig. 1a) was roughly estimated in a semi-quantitative manner by the area affected. Based on various test-plot measurements in Switzerland, three intensity classes for sheet erosion were defined (light = 0.5 t $ha^{-1}$; moderate = 1.0 t $ha^{-1}$; severe sheet erosion including small rills < 2 cm depth = 1.7 t $ha^{-1}$). The assignment to this classes was performed visually according to visible flow traces. The erosion data from the monitoring period of 1987–1989 were taken from Mosimann et al. (1990). From the hydrological year 1997/98–2016/17, an experienced surveyor recorded a total of 2165 erosion systems in 115 area-wide field inspections. The 20-year measurement series was divided into two 10-year monitoring periods: from 1997/98–2006/07 and from 2007/08–2016/17 (Prasuhn, 2020). The accurate methodical procedure is documented in detail in Prasuhn (2011, 2012, 2020) and Prasuhn and Grünig (2001).

### 2.4. Statistics

Statistical analysis such as linear regression analysis, determination of coefficients of variation and p-values were performed using standard procedures in R (R Core Team, 2019) and Excel (Microsoft, Redmond, USA).

## 3. Results

### 3.1. Land use and soil management

In Switzerland, there are no more typical crop rotations but rather specific crop sequences. Farmers usually decide annually which crop they grow next based on market prices, personal boundaries, or weather conditions. However, within the framework of the PEP, there are various legal requirements and restrictions for crop sequences and soil cover, mainly for phytosanitary reasons. Therefore, there are mostly versatile crop sequences with four to six crops, and monocultures are restricted. Additionally, the farm structures—mostly relatively small mixed farms with 16.7 ha area—promote crop diversity. The temporary grasslands and cover crops are often cultivated as intermediate fodder crop.

In the study region, the number of arable fields decreased by about 30%, from 259 fields in 1987–89 to 182 fields in 2016/17. Ten fields (11 ha) were converted into permanent grassland between 1987 and 1997, and another 22 fields (20 ha) between 1997/98 and 2010/14. A total of 46 arable fields (18%) were merged and cultivated in the same way. Consequently, the average plot size of arable fields in the study area increased from 1.07 ha in 1987–89 to 1.31 ha in 1997–99 to 1.35 ha in 2010–14. About a quarter of the crop rotations changed considerably due to farm conversions or merging. Thus, the agricultural structure in this area altered.

The most widely grown crop is winter wheat (*Triticum aestivum* L.) (Fig. 2). However, the cultivation of winter wheat has decreased from 25% (1987–89) to 17% (2010–14). Temporary grassland is widespread with around 19%, followed by maize (*Zea mays* L.) (16%), sugar beet (*Beta vulgaris* L.) (13%), winter barley (*Hordeum vulgare* L.) (8%), and potatoes (*Solanum tuberosum* L.) (7%). The conversion from arable land to permanent grassland accounted for 5% by 1997–99% and 12% by 2003–09.

Most of the area was cropped during winter (Fig. 3), either with winter cereals (33%), cover crops (20%), or temporary grassland (27%). However, in 1987–89, 27% of the area was fallow in winter (ploughed bare soil or stubbles), in 2010–14, only 11% of the area was left fallow.

The tillage practices changed significantly over the five periods (Fig. 4). Whereas almost all soils were ploughed in 1987–89, the share of ploughless tillage techniques increased rapidly afterwards. In the 2010–14 period, only 26% of the main crops were mouldboard ploughed, while 74% of the main crops were cultivated ploughless. Of the main crops, 54% were grown with high efficiency conservation tillage practices, such as mulch seeding > 30% soil cover, strip-till, or no-till.

### 3.2. Erosivity and soil cover

The average annual erosivity of rainfall in the Swiss Plateau is 152 kJ mm $m^{-2}$ $h^{-1}$. In the two periods 1997/98–2006/07 and 2007/08–2016/17, the average erosivity was in the same order of magnitude (154 and 149 kJ mm $m^{-2}$ $h^{-1}$, respectively (Prasuhn, 2020). The highest erosivity of rainfall occurs in the summer months from May to September, with 70% of the annual erosivity (Fig. 5). Hence, the highest erosivity was reached in August, with 22.2% of the annual erosivity, followed by July (15.6%) and June (11.6%).

Fig. 6 shows the pattern of soil cover for the crop stage periods for the C-factor calculation: sowing (0% cover), 10%, 50%, and 75% cover and harvesting (assumption 100% cover) for the main crops. Ploughing was adopted. Harvest residues, such as stubble, mulch, and cover crops, were included later as sub-factors in the calculation of the C-factor.

Winter oilseed rape is sown in summer and reaches high soil cover over the winter. Winter barley is sown earlier compared to winter wheat and enters the winter with a higher cover than winter wheat. In spring-sown crops, summer wheat reaches a sufficient soil cover of 30% by the end of April, while potatoes reach such an effective soil protection later in mid-May and silage maize in mid-June. July and August, revealing the highest erosivity of rainfall (Fig. 5), have well-developed spring-sown crops and show a high coverage. At this time, also crops sown in summer

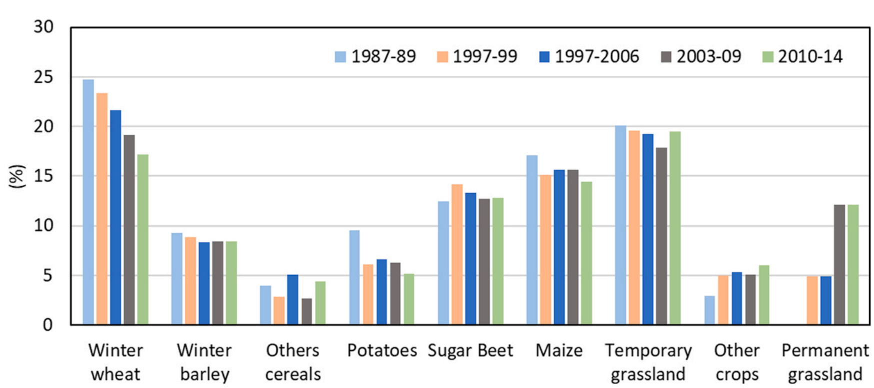


**Fig. 2.** Distribution of the main crops over the five periods in the study area (276 ha).

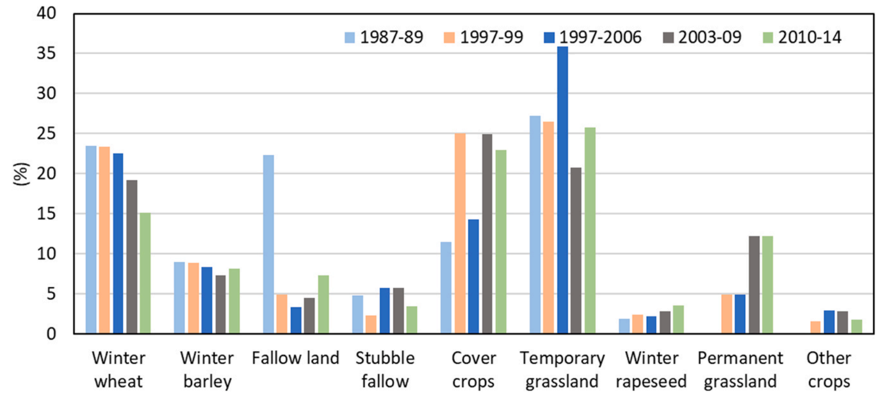


**Fig. 3.** Distribution of the most important winter crops and land uses in the inter-cropping period over the five periods in the study area (276 ha).

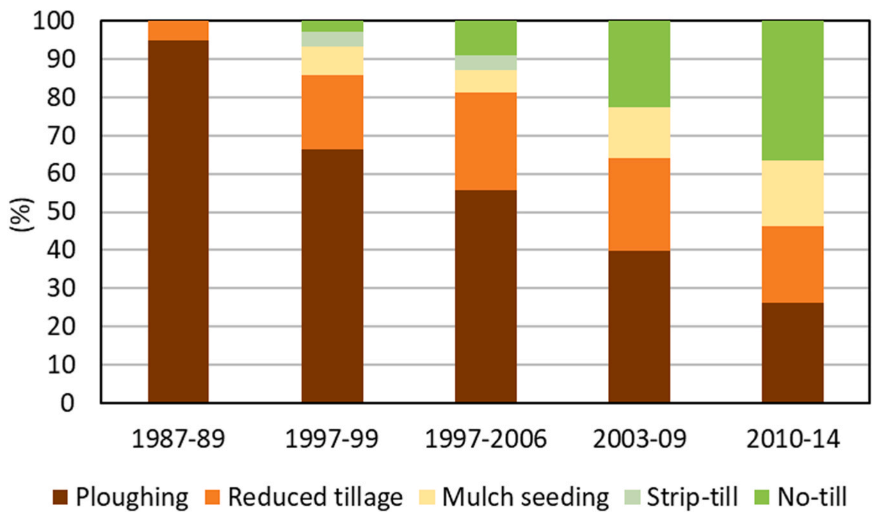


**Fig. 4.** Tillage practices of the main crops in the five periods on the arable land of the study area. (2003–09 and 2010–14, no specific data on strip-till and no-till was available, combined recorded as no-till).

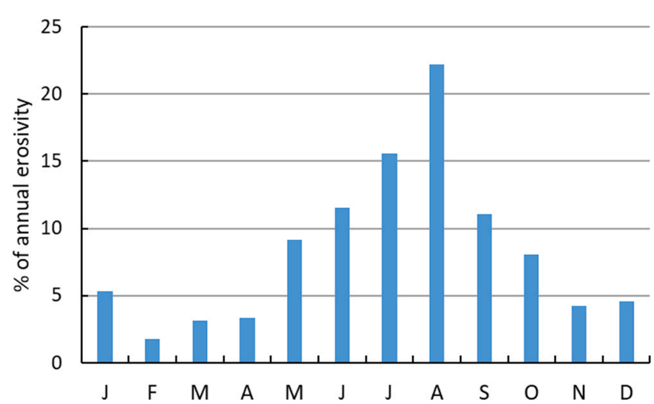


**Fig. 5.** Monthly distribution of the erosivity index R in the Swiss Plateau, with an average annual erosivity R = 152 kJ mm $m^{-2}$ $h^{-1}$. Data from Mosimann and Rüttimann (2006a).

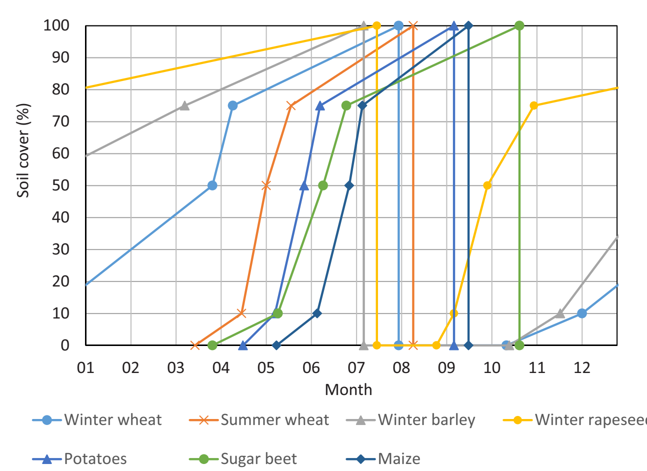


**Fig. 6.** Distribution of soil cover of the main crops at different crop stages: sowing (0%), 10%, 50%, 75%, and harvest (100%) when ploughing. Ground cover by crops without residues or cover crops. Data from Mosimann and Rüttimann (2006a).

or autumn are harvested and erosion control is achieved by leaving the harvest residues (stubble) or by immediately sowing a cover crop.

Concerning the measured soil loss data for the period 1987–89, less detailed information was available from Mosimann et al. (1990). Thus, in the following, the measured soil loss values of the periods 1997/98–2016/17 were analysed in detail. From 1997/98–2006/07, mean soil loss amounted to 0.75 t $ha^{-1}$ $yr^{-1}$. At 0.07 and 0.12 t $ha^{-1}$ $yr^{-1}$, respectively, the mean soil loss rate in mulch-seeding and no-tillage fields was more than an order of magnitude lower than that under plough tillage (1.24 t $ha^{-1}$ $yr^{-1}$) (Prasuhn, 2012). From

2007/08–2016/17 the mean soil loss was significantly lower at 0.20 t ha$^{-1}$ yr$^{-1}$ (Prasuhn, 2020). In both periods, the soil loss rates showed high temporal and spatial variability. Most of the 102 rainfall events with visible erosion between 1997/98 and 2016/17 occurred in March and June. Few erosion events took place in October, December, and January (Fig. 7). Most of the soil loss was in November, with 20% of total soil loss. In November, continuous rainfall is common and soils are frequently saturated. At this time, winter cereals, especially after late-harvested previous crops, generally have an insufficient soil cover. High soil erosion also occurred in March and August. Erosion from snowmelt often occurs in early March, and winter fallow fields are especially susceptible to erosion at this time. In mid-March, the first tillage operations took place for spring-sown crops. At this time, the soil is both loosened and poorly covered. In August, erosivity is highest due to summer thunderstorms. At this time, the harvest of cereals and other crops is already over and newly sown cover crops still have a low soil cover. Low soil erosion was observed in October, December, and January.

Out of the 4060 fields observed from 1997/98–2016/17, 907 fields or 22% suffered from soil loss. Because some fields were split to grow two different main crops in one year, the number of affected fields with different crops was slightly higher, with 1031 fields. Of the total 5300 ha of observed area (265 ha * 20 years), fields with an area of 1867 ha showed erosion, i.e. 35% of the area was on average affected by erosion. However, the area directly affected by erosion was much smaller because, often, only specific regions of a field were affected (Prasuhn, 2020).

About one-third of the total soil loss over 20 years originated from fields with winter wheat, 23% from fields with potatoes, and 14% from winter fallow (Fig. 8). All other crops contributed relatively little to the total soil loss. The number of eroded fields was also highest for winter wheat, followed by winter fallow, sugar beets, and potatoes (Fig. 8). The highest erosion rates per field affected by erosion were found in winter triticale (×*Triticosecale*) (2.35 t ha$^{-1}$ yr$^{-1}$) and potatoes (2.34 t ha$^{-1}$ yr$^{-1}$) (Fig. 9). Additionally, winter wheat, winter fallow, maize, and vegetables had an average erosion rate of > 1.0 t ha$^{-1}$ yr$^{-1}$ per eroded field. Winter barley, winter oilseed rape, temporary grassland, sugar beets, and other crops had lower soil losses < 1 t ha$^{-1}$ yr$^{-1}$ per eroded field.

Regarding the 265 ha study area, winter wheat showed the highest soil losses, with 0.151 t ha$^{-1}$ yr$^{-1}$ (Fig. 9). However, winter wheat was also the crop most frequently cultivated (Fig. 2). Potatoes, which were less often cultivated, also had a high soil loss of 0.107 t ha$^{-1}$ yr$^{-1}$. Note that the values refer only to fields affected by erosion.

Fig. 10 shows the annual distribution of the mapped soil loss in the study area and the annual area share of the corresponding municipalities with conservation tillage (reduced tillage, mulch seeding, strip-till, and no-till). The soil loss shows a large annual variability (Prasuhn, 2020). The area share of conservation tillage methods increased continuously from 1997/98 until 2014/15. Although participation increased with the

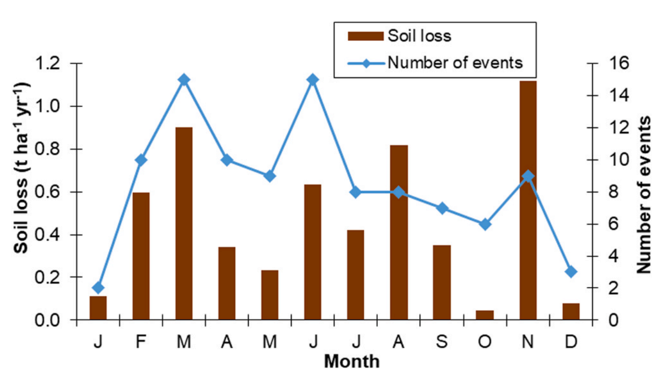


**Fig. 7.** Mean soil loss per month and number of rainfall events with erosion per month in the period 1997/98–2016/17 in the study area.

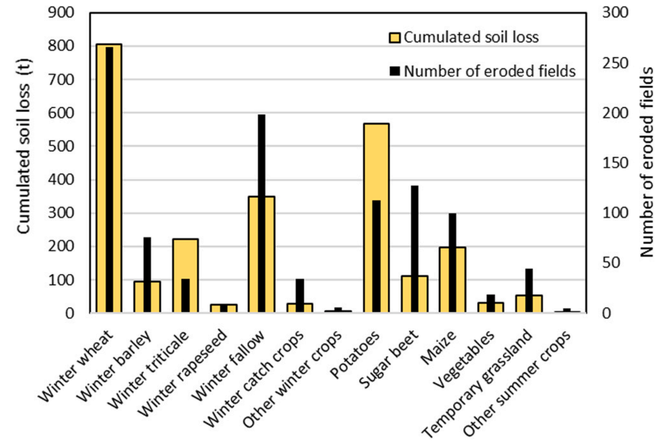


**Fig. 8.** Total soil loss in tonnes in the period 1997/98–2016/17 for the different crops (grey bars) and the number of eroded fields (black bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

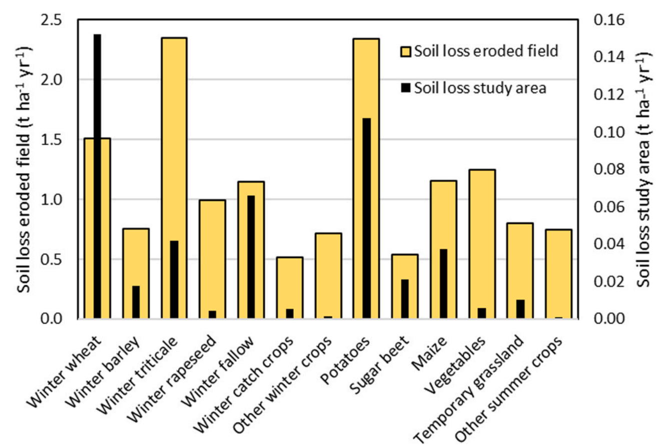


**Fig. 9.** Soil loss in the period 1997/98–2016/17 for the different crops based on the area of the eroded fields of each crop (grey bars) and based on the total study area of 265 ha (black bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

duration of the first cantonal promotion programme from 1996 to 2009, the area share was low and amounted to 5.6% on average. With the start of the cantonal soil support programme in 2010, a significant increase was observed. Overall, the area share in period 2007/08–2016/17 averaged 58.4% with a maximum of 84.8% in 2014/15 and slightly decreased from 2015/16 onwards. From 2014, financial incentives for conservation tillage were provided at a national level. A correlation between the yearly soil loss and the annual areal share of soil conservation treatment over 20 years showed a medium inverse correlation of –0.54 ($p < 0.05$). In period 1997/98–2006/07, the mean annual soil loss (0.74 t ha$^{-1}$ yr$^{-1}$) exceeded three times that of period 2007/08–2016/17 (0.20 t ha$^{-1}$ yr$^{-1}$), while the share of land under soil conservation in period 1997/98–2006/07 (5.6%) was less than one-tenth of that of period 2007/08–2016/17 (58.4%).

### 3.3. Calculated C-factors

From period 1987–1989, the mean C-factor of the 200 examined fields was 0.138 (median), with a relatively large variance (Fig. 11, Table 1). The C-factors decreased by –62% (mean) and –70% (median) significantly over the five periods studied. The decrease in the medians of the C-factors was –31% between 1987–1989 and 1997–1999, –2%

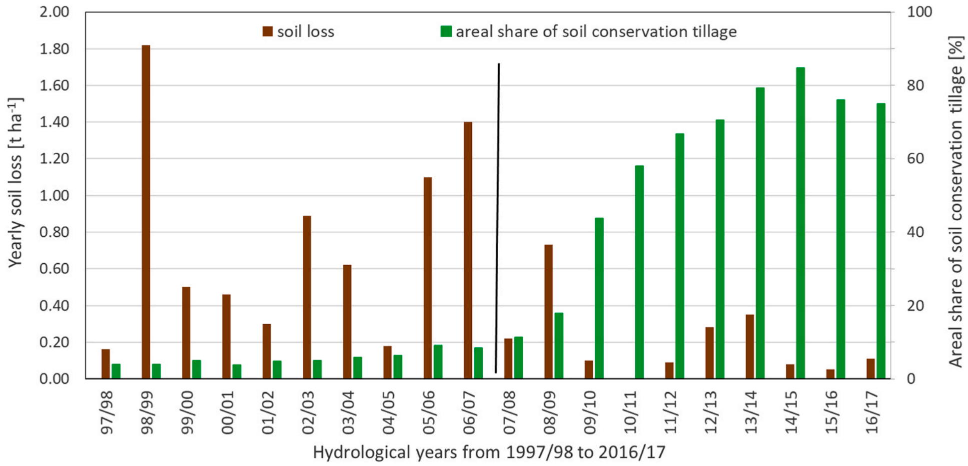


**Fig. 10.** Average yearly measured soil loss (t $ha^{-1}$) in the study area (265 ha) and areal share of soil conservation tillage (%) in the region (1400 ha) for hydrological years in the period 1997/98–2006/07 and the period 2007/08–2016/17.

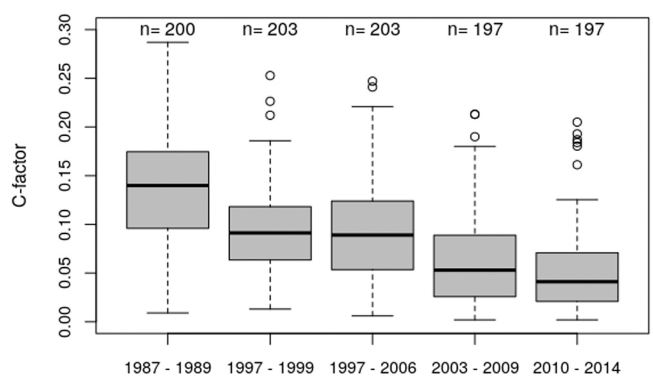


**Fig. 11.** Box plots of the calculated C-factors of the fields studied for five different periods. Boxes indicate median and 25% and 75% quantiles, while whiskers indicate 5% and 95% quantiles.

**Table 1**
Statistical description of the C-factor values of the investigated fields for the five different periods.

| | 1987–89 | 1997–99 | 1997–2006 | 2003–09 | 2010–14 |
|---|---|---|---|---|---|
| Number of fields | 200 | 203 | 203 | 197 | 197 |
| Mean | 0.136 | 0.094 | 0.092 | 0.062 | 0.050 |
| Median | 0.138 | 0.091 | 0.089 | 0.053 | 0.041 |
| Maximum | 0.287 | 0.253 | 0.247 | 0.213 | 0.205 |
| Minimum | 0.009 | 0.013 | 0.006 | 0.002 | 0.002 |
| Standard deviation | 0.059 | 0.041 | 0.052 | 0.046 | 0.041 |
| Coefficient of variation (%) | 43.1 | 44.0 | 56.3 | 74.7 | 80.6 |

between 1997–1999 and 1997–2006, –32% between 1997–2006 and 2003–2009, and –19% between 2003–2009 and 2010–2014. In 2010–2014, the C-factor was low at 0.041 (median). Even the maximum value of the field-level C-factor slightly decreased from 0.287 (1987–89) to 0.205 (2010–14). The different durations of the survey periods and the different time intervals between the periods and the slightly different numbers of fields should be considered when interpreting these results.

A comparison of the C-factors for the individual fields between the five periods showed no clear relationship (Fig. 12). However, all figures showed a decrease in the C-factors for most fields. Nevertheless, there were also a few opposite trends.

Between 1987–89 and 1997–99, the C-factor decreased by 74% of the plots and increased by 26% (Table 2). Overall, this resulted in a mean decrease in the C-factor value of –0.042 or –31% compared to 1987–89. Between 1997–99 and 1997–2006, there were insignificant changes in the mean values. The C-factor increased and decreased for about the same number of fields. However, the period 1997–99 was part of the period 1997–2006. Between 1997–2006 and 2003–09, the C-factor decreased by 82% of the plots and increased by 18% of the plots. The average decrease in the mean C-factor value was –0.030, which is slightly less than the decrease between the first two periods. Between 2003–09 and 2010–14, the decrease in the C-factor was smaller for both the number of plots and the mean C-factor value. In 56% of the plots, the C-factor decreased. However, in 33%, it increased, and in 11%, it remained constant (permanent grassland). Over the whole period from 1987–89 to 2010–14, the C-factor decreased in 91% of the plots and increased in 9%. The mean C-factor value decreased by –0.085% and 62%, respectively.

The mean change in the C-factors of the individual plots from period to period decreased and amounted to –0.085. Thus, the largest changes occurred between 1987–89 and 1997–99 and then decreased continuously. The mean decrease for plots with decreasing values was –0.071 at the beginning, followed by –0.040 or –0.041, and finally –0.038, i.e. the average decrease became smaller over time. The mean increase in plots with increasing values was significantly less than the mean decrease in plots with decreasing values. Therefore, the benefits of soil protection exceeded its drawbacks due to intensification of land use. The mean increase for plots with increasing values was initially +0.041, followed by +0.040 or +0.027 and finally +0.030, i.e. the average increase was slightly smaller.

The C-factors were subjected to variations over the selected time spans (Table 3). At 84.7%, the C-factor fluctuated regarding increase and decrease within the five periods. In no single plot did the C-factor increase over all five periods, but in 11.3% of all plots, there was a continuous decrease. In 3.9%, there was no complete time series due to missing data.

### 3.4. Comparison of C-factors and soil erosion

No correlation was found between the calculated C-factors and the mapped soil loss of the 203 plots for the corresponding period or for the whole mapped period 1997/98–2006/07 and 2007/08–2016/17 (data not shown). The C-factor reflects a long-term average value, while the measured soil loss reflects the real situation during the respective measuring period.

In contrast, comparing the calculated C-factors and the measured soil loss for the five different periods over the whole study area, clear correlations are obvious (Fig. 13). The C-factors decreased continuously

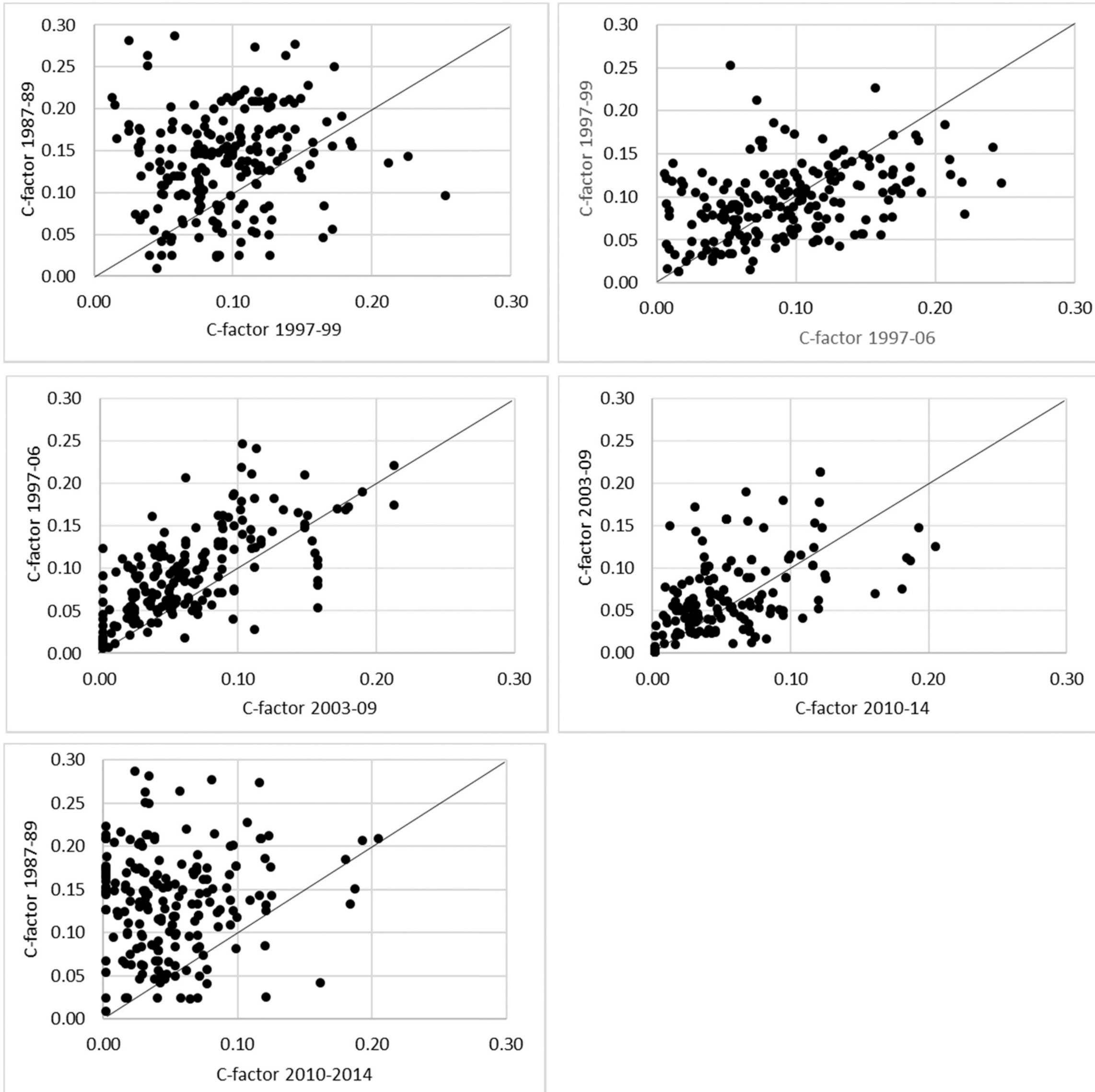


**Fig. 12.** Comparison of the C-factors of individual fields in the periods 1987–89 and 1997–99 (top left, 1997–99 and 1997–2006 (top right), 1997–2006 and 2003–09 (middle left), 2003–09 and 2010–2014 (middle right), 1987–89 and 2010–14 (bottom left) (n = 197).

**Table 2**
Differences in the C-factor values between the different periods and over the entire period.

| | 1987–89 vs 1997–99 | 1997–99 vs 1997–2006 | 1997–2006 vs 2003–09 | 2003–09 vs 2010–2014 | **1987–89 vs 2010–2014** |
|---|---|---|---|---|---|
| Number of fields | 200 | 203 | 197 | 197 | **196** |
| Change of C-factor values (%) | −31.0 | −2.3 | −32.2 | −18.9 | **−62.9** |
| Number of fields with decreasing C-factor | 148 | 96 | 161 | 110 | **179** |
| Number of fields with increasing C factor | 52 | 106 | 35 | 65 | **17** |
| Number of fields with constant C-factor | 0 | 1 | 1 | 20 | **0** |
| Average shift of C factor value | −0.042 | −0.002 | −0.030 | −0.012 | **−0.085** |
| - for fields with decreasing C-factor | −0.071 | −0.040 | −0.041 | −0.038 | **−0.097** |
| - for fields with increasing C-factor | 0.041 | 0.040 | 0.027 | 0.030 | **0.034** |

over the five periods. The mapped soil loss 1987–89 was in the same order of magnitude as in 1997–06 (0.71 t ha$^{-1}$ yr$^{-1}$ and 0.75 t ha$^{-1}$ yr$^{-1}$, respectively). However, the two periods were brief and did not sufficiently reflect the high temporal variability of soil erosion (Prasuhn, 2020). From 1997–99 onwards, soil erosion and the C-factors decreased continuously. The average measured soil loss in period 2007/08–2016/17 amounts to only 27% of the soil loss in period 1997/98–2006/07, i.e. soil erosion was reduced by more than two-thirds. The calculated C-factors of all mapped fields in the period from 1997–1999 to 2010–2014 decreased by 46% (mean) and 55% (median), not quite as much, but still significant.

**Table 3**
Number of fields with variations in the C-factor values over the five periods.

| | Number of fields | (%) |
|---|---|---|
| Continual decrease of the C-factor value | 23 | 11.3 |
| Continual increase of the C-factor value | 0 | 0.0 |
| Alternate C-factor value | 172 | 84.7 |
| No complete time series | 8 | 3.9 |
| | 203 | 100 |

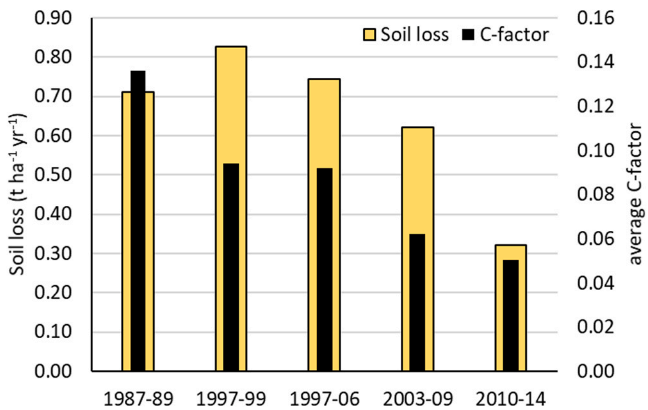


**Fig. 13.** Comparison of the average measured soil loss rates and calculated C-factor values for the five different investigation periods in the study area.

## 4. Discussion

### *4.1. Land use and management changes*

In Switzerland, a period of landscape development started in 1993 with a change in the agricultural political system and new legal regulations for soil and water conservation. New agricultural support measures and programmes—particularly, various requirements for adequate soil protection (crop rotation, cover crops) and support programmes for conservation tillage—are influencing current landscape developments (Prasuhn and Weisskopf, 2004). Land use changes can largely impact the amount of soil loss and on the calculated C-factors. Bakker et al. (2008) modelled for four different regions in Europe (Portugal, France, Greece, and Belgium) that a de-intensification of land use, such as the conversion of arable land to forest, led to lower C-factors and therefore lower soil loss and sediment yield. The conversion of arable land to grassland is also considered amongst the most efficient erosion control measures, especially when implemented in fields prone to erosion (Van Rompaey et al., 2007). However, this measure is usually associated with changes in farm structure and productivity and with financial losses for the farmer. In the study area, 31 ha or 11% were converted to grassland or ecological compensation areas between 1987 and 2014. However, these areas were not particularly erosion prone, neither with regard to mapped erosion nor to modelled erosion risk. Rather smaller fields in areas unfavourable for cultivation were converted. Additionally, Cebecauer and Hofierka (2008) stressed that the effect of agro-environmental policy measures regarding soil erosion and sediment transport is related not only to the percentage of set-aside arable land but also to the local conditions and spatial configuration of set-aside plots.

The applied carry-over effects considered the effects of the preceding crop on the succeeding crop (Auerswald et al., 2003). A high proportion (> 50%) of leaf crops (sugar beet, potato, maize, etc.) in crop rotations leads to a stronger pressure on soil structure, partly because of intensive seedbed preparation and slow initial development, and partly because of late harvest of leaf crops with heavy machinery, which generally increases erosion risk. For example, cereals and oilseed rape after potatoes or sugar beets have an increased erosion risk due to intensive soil disturbance and compaction during the harvest. Therefore, harvesting should not occur under unfavourable soil conditions. In contrast, residual effects of turned sod from temporary grassland increase aggregate stability and soil organic matter content in the first two years after ploughing up of temporary grassland, resulting in a lower vulnerability to erosion in crops grown during this period. In the majority of the plots, crop rotations including between 20% and 40% root crops were cultivated. The critical threshold of 50% of root crops (Schwertmann et al., 1990) was exceeded by only 5% of the plots. In these cases, higher C-factor values were calculated to account for the carry-over effect. On approximately 20% of the plots, crop rotations without forage production were practised. This means that about 80% of the fields' temporary grassland occurred in the crop rotation. Because of the carry-over effect of sod residuals from temporary grassland, lower C-factor values were calculated (Auerswald et al., 2003; Wischmeier and Smith, 1978).

During the period 1987–1989, direct sowing and strip tillage techniques were not yet operational and were unused. In some cases, reduced tillage was applied. The increase in conservation tillage was due to technical progress, innovative farm contractors, etc., but mainly to financial incentives through special support programmes (Prasuhn, 2020).

### *4.2. Rainfall erosivity and soil cover*

Undoubtedly, the highest proportion of annual mean erosivity was recorded in August—contrary to Bavaria, Germany, where it is in June (Schwertmann et al., 1990), and to Austria and Belgium, where it is in July at most monitoring stations (Strauss et al., 1995; Gabriels et al., 2003). The seasonal distribution of soil erosion, however, shows, on average, a largely balanced pattern. Prasuhn (2010) did not find a statistically significant relationship between annual erosion and the annual amount of precipitation or erosivity of the precipitation events. Evans (2017) supported this observation. High soil erosion occurred in all seasons in the study area (Prasuhn, 2012, 2020), and large events with high erosivity may have low erosion if all crops had sufficient soil cover. The temporal interaction between erosion and other factors, such as crop species, soil cover by crops and crop residues, tillage, or soil moisture, is crucial to determining the amount of erosion.

The chronological sequence of the soil cover shows sufficient soil cover in the winter period of oilseed rape and winter barley, while winter wheat only reaches sufficient cover in early spring. Büchi et al. (2016) also showed that in Switzerland, winter oilseed rape and winter barley showed a high cumulative soil cover, whereas winter wheat had a high number of days with insufficient soil cover. During the erosive summer months, spring-sown crops have reached a high cumulative soil cover > 30%, thus providing adequate erosion control. Cereals and oilseed rape are harvested at a time of high erosivity. A following stubble fallow provides acceptable erosion protection. However, especially after the harvest of potatoes, when no soil protection is present and soil structure deteriorates, there is a high erosion risk.

### *4.3. Cultivated crops and support programmes*

In winter wheat and winter triticale, high soil losses were measured. Both often followed sugar beets and potatoes in the study area. Sugar beets were harvested very late, and heavy soil compaction by sugar beet harvesters occurs. Additionally, only a few easily degradable crop residues remained on the field. Due to the late sowing date of wheat, soil cover over the winter was insufficient. Consequently, much erosion can occur. During potato harvest, the soil structure was diminished. Conservative tillage methods of winter wheat and winter triticale following potatoes, are hardly possible or do not achieve > 30% soil cover. Accordingly, there was often severe erosion of winter wheat and winter triticale following potatoes. This special situation in winter cereals was considered when calculating the C-factors.

In the study area, the changes in tillage practices were closely related to the support programmes. The significant increase in conservation tillage practices to 73.9% in 2010–14 in the study area and 84.8% in 2014/15 in the municipalities of this region resulted in a huge reduction in soil erosion, which has been maintained at a very low level since 2009/10.

### 4.4. Calculated C-factors

The calculated median C-factors in the study area ranged between 0.138 in 1987–1989 and 0.041 in 2010–2014, with a maximum value of 0.287 for a single field and a minimum value of 0.006. Borrelli et al. (2018) found C-factor values in the arable land of the Upper Enziwigger catchment (Switzerland) in a similar order of magnitude, ranging from 0.02 to 0.32. However, the calculated mean annual C-factor of Swiss grasslands was significantly lower at 0.012 (Schmidt et al., 2018). In the study area, the standard deviation (SD) of the C-factor values for 1987–89 was 0.059, and the coefficient of variation (CV) was 43% and changed to SD = 0.041 and CV of 81% by 2010–14. For 40 crop rotations in the Kemmelbeek watershed in Belgium, Gabriels et al. (2003) reported an average C-factor value of 0.34, with a SD of 0.05 and a CV of 15%. Guo et al. (2015) calculated an identical mean C-factor value for 88 crop rotation systems in China as Gabriels et al. (2003) with 0.34, but with a range from 0.15 to 0.74, a SD of 0.12, and a CV of 38%. Both studies showed a higher mean value and lower CV for the C-factor values compared to this study. The crop rotations in the study area are more diverse than in the other two studies, and the C-factor values are on average lower from crop rotations with temporary grassland and conservation tillage practices. The CV of the C-factors increased over time in the study area because crop rotations became more flexible crop sequences.

According to Fiener and Auerswald (2016), the average C-factor for arable land in Bavaria (Germany) had a similar order of magnitude as this study, with 0.13, but with a significantly higher maximum value (range: 0.01–0.45). Significant higher C-factors were mentioned in various studies from other countries: Fernandez et al. (2003); Fu et al. (2006); Cebecauer and Hofierka (2008); Panagos et al. (2020); Ayalew et al. (2021). In other studies, C-factor values were listed for different single crops (Šúri et al., 2002; Zhang et al., 2003; Bakker et al., 2008; Bargiel et al., 2013). The reason for the higher C-factor values in the above-mentioned studies may be the calculation method, which in most cases is not as detailed as in this study. Contrastingly, in other countries, partly less conservative tillage methods exist, less cover crops, no temporary grassland, but instead maize monoculture cultivation, leading to higher C-factor values.

The C-factor values clearly decreased over the five calculated periods from 1987–1989 to 2010–2014 by 62% (mean) and 70% (median). Despite a smaller number of farmers and larger fields, only a few fields (9%) have intensified land use and/or tillage practices regarding an increase in C-factor values. On most fields (91%), the C-factor values have decreased. The decrease can clearly be attributed to the increase in conservation tillage methods. Cover crops, which increased significantly, have numerous benefits in reducing soil erosion or C-factors, as shown by Nyakatawa et al. (2001); Verstraeten et al. (2002); Wall et al. (2002) and Aronsson et al. (2016). Cover crops not only protect the soil in winter but are also a prerequisite for good conservation tillage with sufficient soil cover for spring-sown crops. Leaving crop residues in the field or incorporating cover crops in autumn also resulted in a reduction in soil losses (Verstraeten et al., 2002). However, cover crops sown in the month of highest erosivity (August in Switzerland) can lead to erosion and is therefore not without risk.

Panagos et al. (2015) stated that the implementation of good agriculture and environmental conditions led, between 2003 and 2010, to a reduction in soil loss from arable land in the EU-28 from 3.35 t ha$^{-1}$ yr$^{-1}$ to 2.67 t ha$^{-1}$ yr$^{-1}$ (= −20.2%). The average C-factor was reduced by 19.1% because of combined management practices. The management practice with the greatest impact on soil loss rates was reduced tillage (reduction of the C-factor by 17%). By leaving crop residues in the field, the C-factor was reduced by 1.2% and cover crops by another 1.3%. This estimated long-term average erosion rate decreased by 0.4% between 2010 and 2016 (Panagos et al., 2020). In this period, the mean EU-28 C-factor in arable lands decreased by –0.84%, from 0.2336 to 0.2316. The increase in land under soil conservation practices and the land cover change contributed to decreasing the mean C-factor by –0.7% (from 0.1043 in 2010 to 0.1036 in 2016).

Reduced tillage or no-till practices are effective in reducing soil erosion by water (Seitz et al., 2020). Nyakatawa et al. (2001) concluded that C-factors under conventional tillage under cotton-winter fallow cropping were about four times greater than those under no-tillage. Fu et al. (2006) modelled soil loss and C-factors with RUSLE for a catchment in south-eastern Washington. Their results showed that the average soil loss decreased from 17.67 to 3.89 t ha$^{-1}$ yr$^{-1}$ for arable land under the no-till scenario. The authors identified that a major reason why the C-factor was significantly reduced by no-tillage practice was that no-tillage prevents rill generation and rill erosion. Preiti et al. (2017) confirmed these findings in a hilly area of Calabria. They found that cropping systems managed by conservation or alternative tillage reduced soil erosion by an average of 67%, compared with conventional tillage.

### 4.5. Comparison of calculated C-factors and measured soil loss

Comparing the C-factors of the individual fields of the five periods with the mean mapped soil loss of the corresponding periods did not show any correlation in this study. There is even no correlation between the C-factor over 10 years from 1997– 2006 and the soil erosion from 1997/98–2006/07 for individual fields. Other factors (LS-, R-, K-, and P-factors) are also important for the actual soil loss rates. The time span for the C-factor calculation is also brief. The C-factor includes the long-term average of R-factor. However, the mapped erosion captures the real conditions of a certain field. The interaction of weather, soil cover, and soil status is essential for soil loss rates. Further reasons for the discrepancy between the measured soil loss and calculated C-factors for individual plots are the various triggers of soil erosion, which can be limitedly reproduced by the USLE/RUSLE. Potatoes, for example, showed very high crop-specific soil loss in the study area. High linear soil erosion often occurs after a breakthrough in potato ridges (Fig. 1b) (Prasuhn, 2020). However, this is not considered in the C-factor and should in the future be integrated into the C-factor calculation. The SLR for potatoes are comparatively low. Chow and Rees (1994) required significantly higher C-factors for potatoes. Erosion in pathways, such as traffic lanes or on headlands, was identified as a main driver of soil erosion (Prasuhn, 2011, 2012, 2020). This cannot be considered for the C-factor calculation, therefore, correction factors or special SLR values for traffic lanes or headlands should be implemented into the C-factor calculation in the future. However, this would require further measurements.

However, the estimation of C-factors used may limit specificity compared to real soil cover due to intrinsic assumptions and low temporal resolution. New methods based on low- or high-altitude imaging (remote sensing) can deliver canopy cover patterns in high spatial and temporal resolution and therefore may help to improve C-factor inclusion in erosion risk modelling and monitoring. However, satellite-remote sensing methods may be limited regarding soil tillage differentiation and for partitioning small green vegetation and vegetation residue coverage, particularly in early growth stages. Here, drone-based imaging can fill the gap if applicable, at least for advancing knowledge on the model parameters for the C-factors.

At the landscape level, however, there are many fields with different boundary conditions, so there is a relationship between the mean value of the C-factor and the average mapped erosion of the study area. The decrease in the calculated C-factors reflects the reduction in the measured soil loss satisfactorily if one considers that the periods are not identical and additional factors influence the soil loss. However, the decrease in the calculated C-factors can be explained well by the increase in the number of fields with conservation tillage due to participation in conservation programmes.

## 5. Conclusions

This study demonstrated that with the calculation of C-factors over different periods, changes in average soil loss rates for a region can be satisfactorily represented. However, it is important that a more detailed calculation of the C-factors be performed, considering crop rotations or crop sequences, different tillage practices, cover crops, carry-over effects of different crop sequences, current crop stage periods of the region, and locally adapted erosivity values.

Erosion mapping and in-depth calculation of C-factors are both considered to be time-intensive, expensive, and consequently are rarely used. This study showed that such surveys are feasible and produce evidence-based results. Satellite- and drone-based monitoring and mapping may foster improvement of the C-factor and model evaluation regarding actual erosion.

The C-factor calculation enabled us to assess the impacts of agricultural practices and policies on soil erosion risk and simulate trends for future soil loss rates. This is an important benchmark for the assessment of ecological measures, and the calculation of C-factors can be used as an agri-environmental indicator (Prasuhn and Blaser, 2018). The results of the mapping of soil erosion damage confirm the protective effects against soil erosion, which were attributed to soil conservation tillage systems in the model calculations. Comparisons with international studies indicated that the C-values of crop sequence systems were lower in the study area than in Europe, China, and the United States. The reasons for this are well-balanced crop sequences, the incorporation of multi-year temporary grassland and cover crops and the high share of conservation tillage practices in the study area. Alongside the used detailed calculation method considers many sub-factors, e.g. carry-over effects of temporary grassland.

## Declaration of Competing Interest

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

## Acknowledgements

I am very grateful to Andreas Chervet and Regula Schwarz (Soil Protection Service Berne) for providing data for participation in the cantonal programmes and data on land use and C-factors in the periods 1997–2006 and 2010–2014. Furthermore, I want to thank my colleagues Ernst Spiess and Frank Liebisch (Agroscope) for their comments on the manuscript of this paper.

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