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Soil loss due to crop harvesting in highly mechanized agriculture: A case study of sugar beet harvest in northern Germany

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ABSTRACT

Soil loss due to crop harvesting (SLCH) is a globally occurring and underestimated process that promotes soil degradation. Despite its negative effects on soil functionality and fertility SLCH has received comparatively little scientific attention to date. In Europe, sugar beets hold particular significance due to high production rates, while research in commercial mechanized farming of sugar beets is lacking. The aim of this study is to measure SLCH for sugar beets including nutrient and SOC losses using typical state of the art harvesters and compare that values to estimated SLCH provided by sugar beet factories. In addition, we tried to identify crop and soil variables that influence SLCH. Therefore, sugar beets and soil samples were collected for 14 sampling sites over a three-year period in Northern Germany to measure SLCH dependent on different crop characteristics, soil properties and weather conditions. The results indicate that SLCH is 0.064 kg per kg harvested sugar beet (SLCHspec) on the average, which corresponds to a loss of 5.7 Mg ha-1 harvest-1 (SLCHcrop). These numbers are higher than former comparable studies but also of about 83.3% higher than SLCH estimated by sugar beet factories. Additionally, amounts of SLCH considerably varied between years and fields, but also within fields. The most influential variables on SLCH are soil water content (SWC) and clay content, and we also observed that soil properties impact SLCH differently in relation to SWC. Moreover, we estimated that SLCH of sugar beets can lead to significant SOC and nutrient losses, latter resulting in direct costs for farmers of 18–34.4 € ha-1 harvest-1. The results confirm the importance of considering SLCH for soil degradation analyses and estimations and the need for models which spatially assess SLCH from field to global scales. This is important to explore soil conservation measures and strategies to reduce ongoing soil degradation especially in highly mechanized agriculture.

1. Introduction

The unsustainable use of soils is a significant factor contributing to ongoing soil degradation around the globe. Currently, approximately 60% of European soils are classified as unhealthy (Panagos et al., 2024). As a response, the European Commission proposed the Soil Monitoring Law to reverse the current state of unhealthy soils and safeguard soil resources to ensure a secure food supply (European Commission, 2023).

Soil loss due to crop harvesting (SLCH) leads to a depletion of soil fertility and increases production costs (Faraji et al., 2017; Parlak et al., 2021; Parlak et al., 2022). The loss of soil fertility is primarily attributable to the extraction of carbon-enriched topsoil and essential nutrients posing a challenge to agricultural sustainability and maintenance of soil health (Oztas et al., 2002; Ruysschaert et al., 2005). According to current knowledge, measured SLCH rates in the EU for machinery harvest are in average ~6.8 Mg ha harvest (Kuhwald et al., 2022) and potentially exceeding soil formation rates (0.3–1.4 Mg ha−1 yr−1; Verheijen et al., 2009). Consequently, SLCH emerges as a critical soil degradation process, characterized by soil loss rates that can be as high as those observed for water (e.g. 2.67 Mg ha^{-1} year^{-1}; Panagos et al., 2016) and wind erosion (0.53 Mg ha^{-1} year^{-1}; Borrelli et al., 2017), which is also why SLCH is considered as one of the indicators for

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assessing soil degradation in the proposed Soil Monitoring Law (European Commission, 2023).

SLCH occurs during the harvest of root and tuber crops, i.e. during harvesting of crop components that are in direct contact with the soil, such as cassava (Manihot spp.), potatoes (Solanum tuberosum L.), yams (Dioscorea spp.), sweet potatoes (Ipomoea batatas (L.) Lam) and sugar beets (Beta vulgaris L.). In total, 8.4% of all arable soils were cultivated with root and tuber crops in 2019 and were thus affected by SLCH (FAO, 2021; Kuhwald et al., 2022), while it is estimated that ~68% of the global arable land may be potentially susceptible to SLCH (Borrelli et al., 2023).

Despite the importance of SLCH as a soil degradation process, only a few studies are available focusing on this topic (Parlak et al., 2016; Ruysschaert et al., 2006). A comprehensive literature review conducted by Kuhwald et al. (2022) reveals a limited focus on specific crops with respectively only 11 and 9 references for sugar beets and potatoes. However, in particular sugar beets contribute to high amounts of SLCH (Poesen et al., 2001; Ruysschaert et al., 2005) which are among the major cultivated root crops in the EU (e.g. Germany, France, Poland) (Panagos et al., 2019). Ruysschaert et al. (2007b) showed that single harvest events can result in a soil loss of 30.1 Mg ha^{-1} harvest^{-1}. The mean soil loss, however, is lower and can range between 1.0 Mg ha^{-1} harvest^{-1} (Li et al., 2006) and 13.8 Mg ha^{-1} harvest^{-1} (Ruysschaert et al., 2005). Sugar beet harvesting in the EU, which mainly takes place in the autumn months (September-December), is strongly promoted by high soil water contents (SWC) due to typically high rainfall and low evaporation during that period, promoting soil adhering to the crops (Panagos et al., 2019; Ruysschaert et al., 2006).

To reduce SLCH, several efforts by manufactures and farmers were made in the last decades. For instance, in mechanized harvest the harvest procedure changed from manual harvest to one row harvest to self-propelled harvesters (Vermeulen, 2001). With this change in harvest technique, cleaning devices were developed and installed at the harvester to clean the sugar beets during the harvest (Ruysschaert et al., 2005; Schulze-Lammers and Strätz, 2003). Based on factory data, Schulze-Lammers and Strätz (2003) showed that these technical developments had contributed to a reduction of SLCH for sugar beets.

In contrast to the continuous development of machines and equipment, studies focusing on the investigation of SLCH from sugar beets are mainly conducted from 2001 to 2008 (Kuhwald et al., 2022), while only four newer studies appeared in the period of 2009–2022 (Faraji et al., 2017; Panagos et al., 2019; Parlak et al., 2021; Tuğrul et al., 2012).For instance, Tuğrul et al. (2012) used data from Turkish sugar beet factories and calculated mean SLCH rates of 3.66–3.86 Mg ha^{-1} harvest^{-1}. Faraji et al. (2017) identified an average soil loss of 2.26 Mg ha^{-1} harvest^{-1} measured from mechanically harvested sugar beets between 2010 and 2012 based on 141 plots from 47 farms in Khuzestan Province in south western Iran. Panagos et al. (2019) calculated the soil loss for the European Union and the single countries of the European Union. The data used for calculating SLCH caused by sugar beet harvesters, however, was taken from former studies (Ruysschaert et al., 2006, 2005). Thus, the effects of new machinery and new cleaning devices were not considered. They modelled an average soil loss of 4.99 Mg ha^{-1} harvest^{-1}. Parlak et al. (2021) investigated soil losses of 1.63 Mg ha^{-1} harvest^{-1} using a one-row harvester on nine different fields during the harvest season of 2019 in Turkey. Thus, there is no study analysing the effects of modern sugar beet harvesters on SLCH.

In addition to the lack of recent studies on SLCH another limitation arises from the fact that most existing research is predominantly based on the use of soil tare measurements from sugar beet factories (Kuhwald et al., 2022). In this case crops are additionally affected by post-harvest processes (e.g. storage, post-harvest cleaning, loading and transport) which changes soil tare between the time of harvest and measurements of the factory. Therefore, SLCH of sugar beet factories is likely to underestimate the true soil loss that occurred on the field where the crops were harvested (Ruysschaert et al., 2004). In addition, factories do not always measure oven-dry soil tare but include unusable crop (crown) tare, where assumptions are needed to correct the values such as e.g. soil moisture and beet top tare (Oztas et al., 2002; Poesen et al., 2001; Ruysschaert et al., 2005; Tuğrul et al., 2012) leading to uncertainties in the results especially when linked to measured soil properties during the harvest. Today only three (Faraji et al., 2017; Parlak et al., 2021; Ruysschaert et al., 2007b) out of eleven studies from Belgium, Iran and Turkey provide information on measured SLCH for sugar beets. Although measuring SLCH under field conditions is time consuming, it has the advantage that SLCH can be linked to the exact soil and harvesting conditions allowing the unbiased linkage to controlling factors.

In response to the identified data gap regarding SLCH as emphasized by Kuhwald et al. (2022) our study aims to contribute towards enhancing our understanding of soil loss due to sugar beet harvest within the context of mechanized agriculture. Therefore, we analysed field measured soil loss caused by self-propelled six row harvester under field conditions for three years. The objectives were (i) to quantify the present soil losses by sugar beet harvest with state-of-the-art harvesters, (ii) to compare measured SLCH from the field with estimated SLCH from sugar beet factories, (iii) to identify the main drivers for SLCH by correlation analysis, in order to develop new regression models operating with easily assessable input data and (iv) to derive SOC and nutrient losses from SLCH to estimate direct economic costs of fertilizer equivalents.

2. Material and methods

2.1. Study area

The study area is located in the Leine-Weser uplands of southern Lower Saxony, Germany and comprises nine arable fields (Fig. 1). Soils in this region are mainly developed from deeply weathered loess of the Weichselian glaciation. Dominant soil types are Haplic and Stagnic Luvisols (IUSS Working Group WRB, 2022) indicating a wide range of soil textures from clay loams and silty clay loams to soils with a sandier texture (Gehrt et al., 2021; LBEG, 2020). According to Köppen & Geiger the study area is in the transition from temperate oceanic (Cfb) to temperate continental climate (Dfb) (Peel et al., 2007). The mean annual temperature is 9.8 ± 0.7 °C with a mean annual precipitation of 701 ± 103 mm for the period from 2008 to 2023 (weather station Alfeld, DWD, 2023).

The fields in the study region are all under intense arable use, where winter wheat (Triticum aestivum L.) is the dominant crop (49.1%) followed by sugar beet (Beta vulgaris L.) with 18.8% and maize (Zea mays L.) with 11.1% (LSN, 2023). Soil tillage is predominantly conducted with mouldboard and chisel plough, while usually no cover crops are grown before sugar beet. The harvest period of sugar beet is usually from late September to mid-November.

2.2. Sampling design and field work

To assess SLCH, soil and sugar beet sampling were carried out during the sugar beet harvest in 2018, 2019 and 2020. The harvest of sugar beets was conducted under different weather conditions as shown by the cumulative precipitation sums in Fig. 2. In total nine different fields containing 14 sampling sites were selected for crop and soil sampling (Table 1). Our site selection considers the variation in clay, silt and sand contents typical for the study region. In five fields, the soil texture was known to vary within the field, which was the reason for taking two samples from these fields. The number of sampling sites varied from three (2020) to six (2018) sites among the years.

Regardless the varying soil conditions, seeding, spraying and tillage practices were the same for all fields. For tillage a chisel plough (non-inversion) with a working depth of 20–30 cm has been used. Sugar beets were sown in seed rows with a distance of 45 cm and a spacing of 20–22 cm along the individual rows. For sugar beet sampling three

Fig. 1. Overview and locations of investigated fields of the study area (Fig. 1).

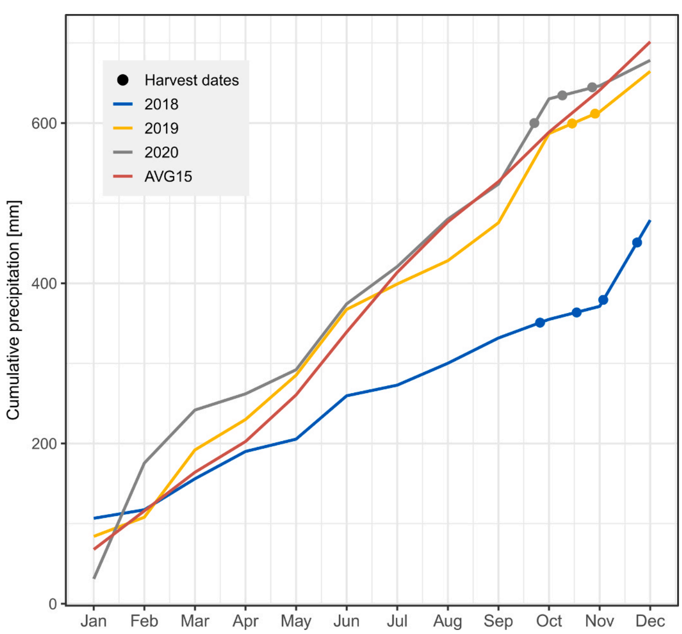

Fig. 2. Harvest dates and monthly cumulative precipitation sums of the three investigated years compared with the 15-year average from 2008 to 2023 (AVG15) from the weather station Alfeld, Germany (DWD, 2023).

different six-row self-propelled harvesters were used (Table 1). The sugar beet harvested by the harvesters went through several cleaning devices to separate the soil and plant residues from the sugar beet before it fell into the trailer body of the harvester. The cleaning circuits of the different harvesters showed small technical variations but were generally very similar.

To obtain sugar beets with adhering soil as realistic as possible, a sampling bag (stable plastic bag of around 1 m^3) were hitched to the front fork of a tractor and placed under the unloading conveyor of the sugar beet harvester (Fig. 3a). For every sampling site one sampling bag was filled with sugar beets to three quarters of its maximum volume during the unloading process in the headlands of the specific field. To avoid fresh mass losses, the harvested beets were taken directly to the laboratory and weighed subsequently. To analyse SWC and further soil properties, disturbed topsoil samples were collected from the sampling sites with a 30-cm auger.

2.3. Laboratory work

2.3.1. Cleaning of sugar beets

All sugar beets were cleaned immediately after harvest using distilled water and brushes to remove all adhering soil from the sugar beets. During the cleaning process bigger soil clods were removed first, and its mass dried and weighed (M_{clods}). At a second step hard and dry stuck coatings were brushed with distilled water. The wash water suspension was stored in a glass cylinder after cleaning and organic material and foliage were removed by sieving. Subsequently, the suspension was dried at 105 °C for at least 72 h. Afterwards, the remaining dry soil was weighed ($M_{suspend}$) with an accuracy of 2 decimal places. M_{clods} and $M_{suspend}$ were summed to calculate the total dry soil and rock fragment mass for each sampling bag (M_{ds+rf}).

Every sugar beet was counted and weighed after cleaning with a balance having an accuracy of one decimal place. Subsequently, an average net weight was estimated for each sampling site (M_{crop}). This procedure was performed separately for each sampling bag. Accordingly, we recorded the number of sugar beets, the total net weight of sugar beets, and the total amount of adhering soil for each sampling site. Furthermore, legs of sugar beets were counted and shares of the sample of each sampling site calculated (legginess). We calculated the crop

Table 1
Sampling site specific information on sampling and harvest of sugar beets.

sample ID	field ID	harvestertype	sampled crops (n)	field area (ha)	seed density (seeds ha^{-1})	crop density (crops ha^{-1})*	harvesting date
01	01	Grimme REXOR 630	110	5.5	101,250	80,737	03.11.2018
02	02	Grimme REXOR 620	148	5	110,500	87,458	17.10.2018
03	02	Grimme REXOR 620	198	5	110,500	87,458	17.10.2018
04	03	Grimme REXOR 620	157	2.8	110,500	94,217	27.09.2018
05	03	Grimme REXOR 620	129	2.8	110,500	94,217	27.09.2018
06	04	Grimme REXOR 620	190	3.4	101,250	70,462	23.11.2018
07	05	Grimme REXOR 620	126	4.5	110,500	62,521	14.10.2019
08	05	Grimme REXOR 620	88	4.5	110,500	62,521	14.10.2019
09	06	Grimme REXOR 630	186	6.8	101,250	81,979	29.10.2019
10	07	Grimme REXOR 620	375	5	110,500	84,828	20.09.2020
11	07	Grimme REXOR 620	172	5	110,500	84,828	20.09.2020
12	08	ROPA Panther 2	334	5.5	110,500	94,489	08.10.2020
13	08	ROPA Panther 2	239	5.5	110,500	94,489	08.10.2020
14	09	Grimme REXOR 630	96	5	101,250	75,723	27.10.2020

*Calculated based on average measured crop weight (Mcrop) and yields provided by sugar beet factories for each field

Fig. 3. Collection of sugar beet samples in the field. a) plastic bag under the unloading conveyor of a sugar beet harvester; b) transport of sugar beet samples from field to laboratory; c) sugar beets with adhering soil in a plastic bag; d) sugar beet before (left) and after (right) cleaning with water.

number for each field (N_{pl}) based on the measured average crop weight of the sampling site and the corresponding crop yield (M_{cy}) provided by the sugar beet factories (Table 1).

2.3.2. Analysis of soil properties

To investigate the effect of soil on SLCH various soil properties were analysed (Table 3). For the determination of gravimetric soil water content (SWC; g g^{-1}) a portion of the samples was oven-dried at 105 °C for 24 h and weighed prior and after drying (Gardener, 1986). The rest of the soil samples were air-dried (35 C°) and rock fragments were separated using a 2 mm sieve.

The soil texture and particle-size distribution were determined using the combined sieve and sedimentation method according to Köhn, which is described by Gee and Bauder (1986) and DIN ISO (1127)7 (2009). Size classes were selected according to the German classification (Ad-hoc-AG Boden, 2005) to determine sand (2.000–63 µm), silt (63–2 µm) and clay (< 2 µm) contents in weight percentages.

Soil pH was estimated using a pH-meter (WTW pH 330i) based on DIN ISO (1039)0 (2005) and electric conductivity (EC) was estimated (WTW Cond 3210) based on DIN ISO (1126)5 (1997).

Calcium carbonate ($CaCO_3$) content representing the inorganic carbon content of the soil was estimated using a “Scheibler Calcimeter” (DIN ISO 10693 1997) while total soil carbon and nitrogen (N) content was determined applying a C/N-Analyzer (EURO EA HEKAtech). Soil organic carbon (SOC) content was then calculated by subtracting $CaCO_3$-content from total carbon content. For the estimation of phosphate (P) calcium-lactate method (VDLUFA, 1991) was conducted using the Perkin Elmer UV/VIS Lambda 2S Spectrophotometers for calibration.

2.4. Calculation of SLCH-values

There are three formulas (1–3) commonly used to describe SLCH (Kuhwald et al., 2022; Ruysschaert et al., 2004), which were used to calculate the soil losses for sugar beet harvest:

$$SLCH_{spec}\ [Mg\ Mg^{-1}] = (M_{ds}+M_{rf}) \cdot M_{crop}^{-1} \quad (1)$$

$$SLCH_{spec/p}\ [g\ p^{-1}] = (M_{ds}+M_{rf}) \cdot N_{pl}^{-1} \quad (2)$$

$$SLCH_{crop}\ [Mg\ ha^{-1}\ harvest^{-1}] = SLCH_{spec} \cdot M_{cy}^{-1} \quad (3)$$

The mass-specific $SLCH_{spec}$ is calculated by dividing the mass of separated dried soil (M_{ds}) and rock fragments (M_{rf}) by the total net mass of sugar beets from the sampling site (M_{crop}). $SLCH_{spec/p}$ represents the plant-specific (p) SLCH in g, where M_{ds} and M_{rf} are divided by the individual crop number (N_{pl}). $SLCH_{crop}$, in contrast, indicates the amount of soil loss per area and harvest [Mg ha^{-1} harvest^{-1}] based on the net crop yield for the particular field (M_{cy}) delivered by the sugar beet factories. The adhering soil per sugar beet ($SLCH_{spec/p}$) was calculated for each sampling site using the proportion between the total soil mass (M_{ds}+M_{rf}) and M_{crop} which was then extrapolated based on the estimated crop number (N_{pl}). It is important to state that based on the applied methodology (chapter 2.3.1) the calculated SLCH amounts reflect the adhering soil removed by the harvesting machine and do not reflect reaccumulated soil after the unloading process which might occur at the beet clamp.

In addition to the single SLCH-values the specific soil–crop contact area (SC_B) was calculated according to the Eq. 4 by Koch (1996):

$$SC_B\ [cm^2\ p^{-1}] = 85.58 + 0.49 \cdot (M_{crop}\ N_{pl}^{-1}) \cdot -9.06 \cdot 10^{-5} \cdot (M_{crop}\ N_{pl}^{-1})^2 \quad (4)$$

The equation accounts for the effect that smaller roots with lower weight are likely to have a larger ratio of contact area to the soil than roots with higher net mass.

2.4.1. Nutrient losses and costs

Based on $SLCH_{crop}$ soil nutrient losses during crop harvesting for N, K and P were estimated using the following equation:

$$NL\ [kg\ ha^{-1}\ harvest^{-1}] = \text{soil nutrient content}\ [kg\ Mg^{-1}] \cdot SLCH_{crop}\ [Mg\ ha^{-1}\ harvest^{-1}] \quad (5)$$

The nutrient losses (NL) were used to derive fertilizer equivalents based on the most common fertilizers in Germany. We used urea with a content of 46% N, triple superphosphate with a P_2O_5 content of 46% (1 Mg P_2O_5 = 0.436 Mg P) and potassium-fertilizer with a K_2O content of 40% (1 Mg K_2O = 0.830 Mg K). As K and K_2O have not been measured in the field we assumed a K-content of 0.3% for the topsoil following the German overview map (BUEK1000N, BGR, 2019). We directly used $SLCH_{crop}$ as rock fragment contents in the entire study were marginal. The fertilizer equivalents were then calculated using Eqs. 6–8:

$$Urea\ [Mg\ ha^{-1}\ harvest^{-1}] = N\ loss\ [Mg\ ha^{-1}\ harvest^{-1}] \cdot 0.46 \quad (6)$$

$$\text{Triple Superphosphate}\ [Mg\ ha^{-1}\ harvest^{-1}] = P_2O_5\ loss\ [kg\ ha^{-1} harvest^{-1}] \cdot 0.46 \quad (7)$$

$$\text{Potassium-fertilizer}\ [Mg\ ha^{-1} harvest^{-1}] = K_2O\ loss\ [kg\ ha^{-1} harvest^{-1}] \cdot 0.4 \quad (8)$$

Finally, economic costs of nutrient losses were estimated using the following equation:

$$Cost\ [€\ ha^{-1}\ harvest^{-1}] = \text{fertilizer equivalent}\ [Mg\ ha^{-1} harvest^{-1}] \cdot \text{unit price}\ [€\ Mg^{-1}] \quad (9)$$

As the unit prices of fertilizers were target to high fluctuations since 2018, we used average prices for the period 2018–2020 (low fertilizer costs; urea = 290.55 € Mg^{-1}, triple superphosphate = 337.08 € Mg^{-1}, potassium fertilizer = 243.56 € Mg^{-1}) and for the period of 2021–2023 (high fertilizer costs; urea = 674.20 € Mg^{-1}, triple superphosphate 645.61 € Mg^{-1}, potassium-fertilizer 430.44 € Mg^{-1}) based on the monthly prices provided by the chamber of agriculture in Germany (LWK, 2024). Additionally, we used Eq. 5 to estimate the losses of SOC and Ca (1 Mg $CaCO_3$ = 0.401 Mg Ca).

2.5. Statistical analysis

Descriptive statistics, correlation and regression analysis were conducted using "R" (4.2.1) to examine the importance of relationships between SLCH and other measured variables. To calculate the relationship between the different SLCH variables ($SLCH_{spec}$, $SLCH_{spec/p}$ and $SLCH_{crop}$) and the different independent variables (soil, management and plant properties) we determined the Pearson correlation coefficients.

Single and multiple regression analysis (linear and non-linear) were additionally performed. Model performance was tested by estimating mean absolute error (MAE) root mean square error (RMSE), coefficient of determination (R^2) and Nash-Sutcliffe-Efficiency (NSE) (Nash and Sutcliffe, 1970). To avoid over-fitting of the models all indices are based on a leave-one-out cross validation (LOOCV). To improve robustness of the models the performance of each equation was further evaluated by checking for homoscedasticity using Breusch-Pagan-Test. Models for multiple regression were fitted and evaluated for all possible combinations of independent variables. To reduce multicolinearity we calculated the variance of inflation (VIF) and tolerance values (1 - R^2 between independent variables). A variance inflation value under 10 and a tolerance value over 0.1 were used as threshold for model fitting (Hair et al., 1995). Finally, we determined the best linear and non-linear models for single and multiple regression. Accordingly, better model fits were judged by increasing adjusted R^2 and NSE and reducing RMSE and MAE.

3. Results

3.1. Soil losses due to sugar beet harvesting

In total, 1278 pieces (p) of sugar beets were collected and processed in the laboratory, which equates to a mean of 169 sugar beets per sampling site. The average weight of a single sugar beet was 1.008 ± 281.1 g with SC_B ranging between 321.4 and 594.4 $cm^2\ p^{-1}$. Crop density ranged from 54,632 to 110,819 p ha^{-1} which resulted in a total crop yield of 435.736 Mg for all 9 fields with an average yield among sampling sites of 80.82 ± 17.71 Mg ha^{-1} $harvest^{-1}$.

Table 2 shows the summarized soil losses and crop properties of the 14 sampling sites. The mean soil loss per crop was 72.7 ± 77.7 g p^{-1} ($SLCH_{spec/p}$) and 0.064 ± 0.07 Mg Mg^{-1} for $SLCH_{spec}$ indicating strong differences among the three individual years (2018: 0.013 ± 0.011 Mg Mg^{-1}; 2019: 0.123 ± 0.046 Mg Mg^{-1}; 2020: 0.089 ± 0.085 Mg Mg^{-1}). For the fields with two sampling sites we could identify different amounts of $SLCH_{spec}$ of 0.006 and 0.021 Mg Mg^{-1} for field 7 and 0.100 and 0.210 Mg Mg^{-1} for field 8 respectively, while the lowest relative difference is in field 5 with 0.127 and 0.166 Mg Mg^{-1}.

Considering the field specific number of crops per hectare, mean $SLCH_{crop}$ was 5.7 ± 6.32 Mg ha^{-1} $harvest^{-1}$, with a minimum of 0.25 and a maximum of 21.1 Mg ha^{-1} $harvest^{-1}$. This resulted in an estimated overall soil loss of in total 274.3 Mg (mean = 30.5 ± 31.0 Mg). In contrast to measured $SLCH_{crop}$, SLCH provided by the sugar beet factory ($SLCH_{cropF}$) is 45.4% lower averaging at 3.11 ± 2.43 Mg ha^{-1} $harvest^{-1}$. All results for each single sampling site are given in the supplement (Table A1).

3.2. Soil properties

Over the three years of investigation, SWC at the 14 sampling sites varied widely from 9.37% to 31.22% (Table 3). Soil texture classes were silty clay (n=2), clay loam (n=1), silty clay loam (n=2), loam (n=4), silt loam (n=5) (Fig. 4).

Sand content varied from 2% to 50%, silt content from 29% to 81% and clay content from 17% to 41% with marginal rock fragment contents of in average ~1%. The average SOC content was at 1.3 ± 0.35%, with a maximum of 2.23%. All soil samples had neutral to slightly alkaline pH-values.

3.3. Correlation and regression analysis

The correlation analysis (Fig. 5) of measured $SLCH_{crop}$, $SLCH_{spec/p}$ and $SLCH_{spec}$ shows strong significant correlations of R > 0.96. However, as $SLCH_{spec}$ is fully reliant on measured values, in contrast to $SLCH_{spec/p}$ and $SLCH_{crop}$ which are partly based on estimated yields from the sugar beet factory, we will focus on $SLCH_{spec}$. Accordingly, legginess and crop density show low correlations, while crop weight, SC_B and yield indicate medium positive correlation coefficients. In contrast the correlation to $SLCH_{cropF}$ is quite high (R = 0.91).

Based on the soil properties (Fig. 6) the highest correlation is for SWC (R > 0.88), indicating that higher SWCs significantly increase SLCH. Additionally, SOC-, $CaCO_3$- and clay-content show strong significant positive relationships with $SLCH_{spec}$. pH_{H2O} and EC have a medium positive correlation with SLCH, although the relationship is not significant. Silt-content has no statistical impact on all SLCH values. Sand indicates the only negative correlation which ranges from −0.39 for $SLCH_{spec}$ to −0.45 for $SLCH_{spec/p}$, while no statistical significance could

Table 2
Summarized soil losses due to crop harvesting (SLCH) of sugar beets and crop properties of the 14 sampling sites (SC_B: beet to soil contact).

Variable	Mean	SD	Min	Med	Max
$SLCH_{spec}$ (Mg Mg^{-1})	0.064	±0.07	0.004	0.027	0.22
$SLCH_{spec/p}$ (g p^{-1})	72.7	±77.7	2.3	33.7	216.8
$SLCH_{crop}$ (Mg ha^{-1} $harvest^{-1}$)	5.7	±6.32	0.25	2.55	21.1
$SLCH_{cropF}$ (Mg ha^{-1} $harvest^{-1}$)	3.11	±2.43	0.48	2.21	6.46
crop density (p ha^{-1})	82,566	±3338	54,632	82,688	110,819
crop weight (g)	1008.0	±281.1	531.4	1017.1	1397.3
legginess (%)	14.44	±7.24	1.54	12.79	26.75
SC_B (cm^2 p^{-1})	481.81	±87.57	321.39	491.16	594.35
crop yield (Mg ha^{-1})	80.82	±17.71	58.89	76.59	105.8

*The properties for each single sampling site are given in the supplementary (Table A1).

Table 3
Summarized soil properties of the 14 sampling sites (SWC: gravimetric soil water content, EC: Electric Conductivity, SOC: Soil organic carbon).

variable	mean	sd	min	med	max
SWC (%)	18.91	±7.8	9.37	19.24	31.22
sand (%)	17.3	±16.5	2.24	9.27	50.05
silt (%)	57.5	±17.1	28.75	54.59	81.17
clay (%)	25.2	±7.65	16.59	23.73	40.71
SOC (%)	1.3	±0.35	0.88	1.22	2.23
$CaCO_3$ (%)	0.08	±0.14	0	0.01	0.47
pH H_2O_2 (-)	7.43	±0.33	7	7.39	7.89
pH $CaCl_2$ (-)	6.91	±0.36	6.29	6.89	7.44
EC (μS cm^{-1})	189.12	±68.3	81.7	197.62	330
N (%)	0.13	±0.04	0.1	0.12	0.23
P_2O_5 (mg kg^{-1})	283.9	±109.11	79.91	285.75	504.61
SOC/clay (Mg Mg^{-1})	0.05	±0.01	0.03	0.05	0.06
SOC/N (Mg Mg^{-1})	9.9	±0.88	8.25	9.75	11.72

*The properties for each single sampling site are given in the supplementary (Table A1).

be detected.

Based on the regression analysis, Table 4 shows the best performing models by only using a single independent variable as predictor for all SLCH values. The results show that SWC as single independent variable performs best as linear model in predicting SLCH ($R^2 = 0.67$, RMSE = 0.039, MAE = 0.033). However, also exponential functions (quadratic and cubic) get nearly similar good results and even perform better if no LOOCV is conducted. The analysis also suggests that clay, EC and SOC are good non-linear predictors and $CaCO_3$-content is a good linear predictor of $SLCH_{spec}$ with $R^2 > 0.4$ and RMSE <= 0.06 (MAE <= 0.05).

Using multiple regression, the best fit to predict $SLCH_{spec}$ was achieved for the variables SWC, clay, yield (all quadratic) and $CaCO_3$ and legginess (linear) with an adj. $R^2 = 0.99$ and an RMSE of 0.008 Mg Mg^{-1} which is a reduction of 75.8% compared to the best linear regression using only SWC (Table 5). For $SLCH_{crop}$ SOC replaces $CaCO_3$ (adj. $R^2 = 0.98$, RMSE of 1.07 Mg ha^{-1} $harvest^{-1}$) as co-variable in the function while the best model for $SLCH_{spec/p}$ consists of SWC, clay (both quadratic), legginess and crop density (adj. $R^2 = 0.94$, RMSE of 18.0 g p^{-1}). Table 5 also shows that regression equations which consider crop related properties (e.g. legginess or yield) perform always better than

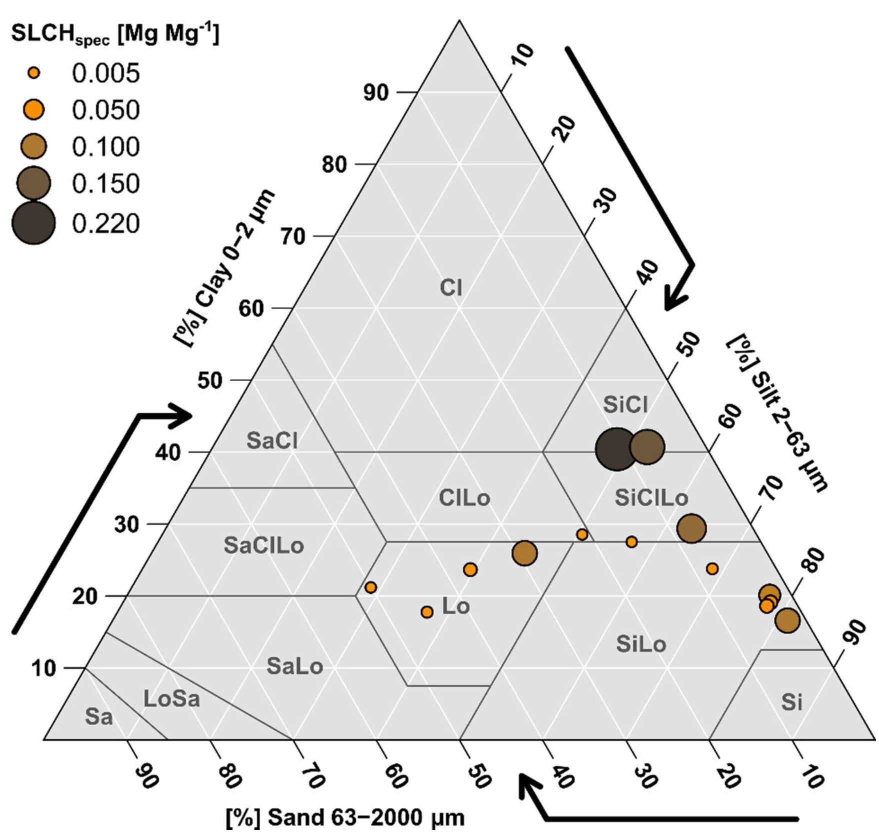

Fig. 4. $SLCH_{spec}$ values based on soil texture classes of the investigated 14 sampling sites according to the USDA soil classification system (USDA, 2017).

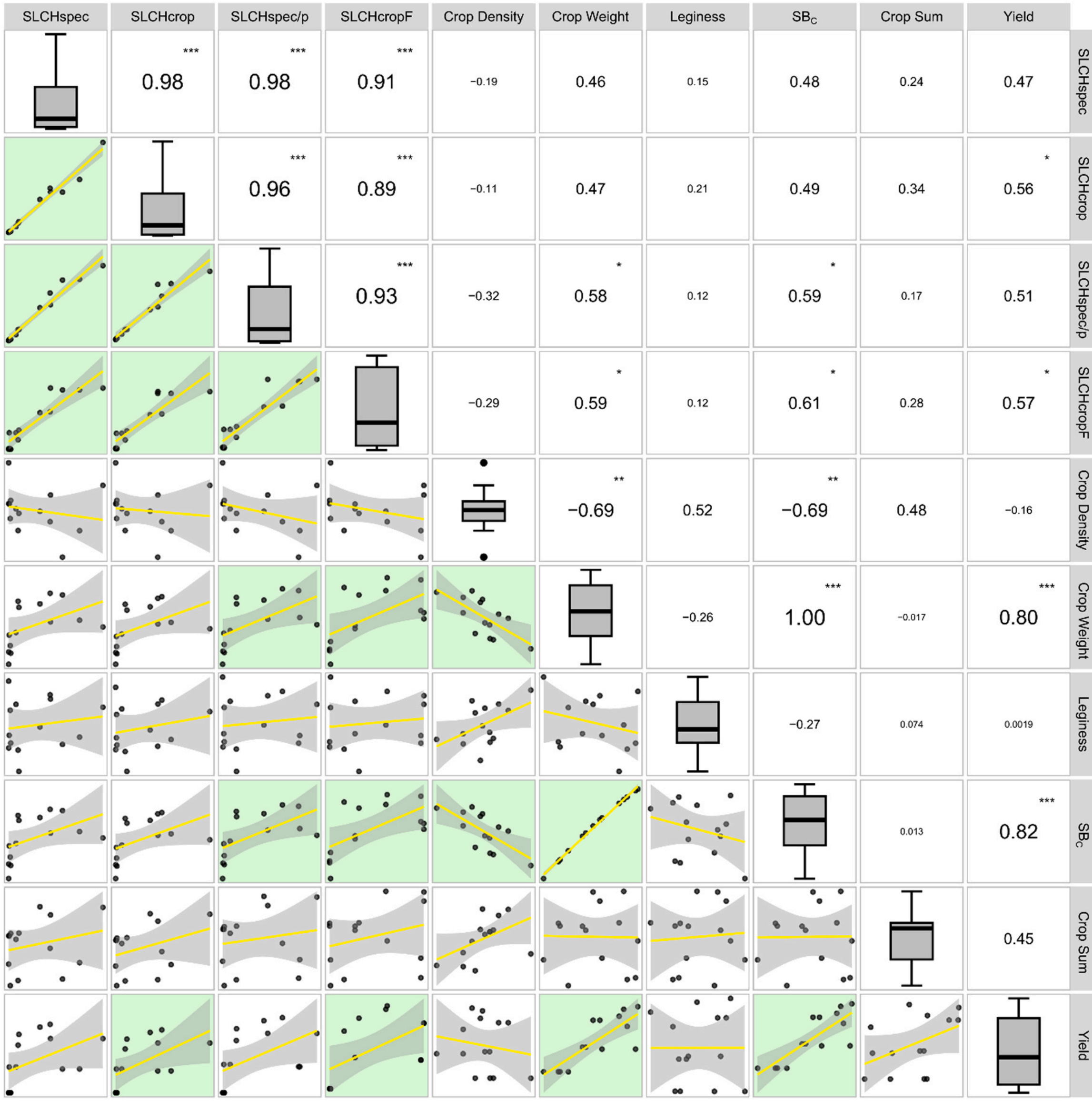

Fig. 5. Pearson correlation coefficients and linear Regression for SLCH values and crop and management related soil properties.

equations which only use soil properties as predictors. However, as crop related properties are not always available, equations only considering soil properties can be more suitable.

3.4. Analysis of nutrient losses and fertilizer costs

Based on $SLCH_{crop}$ nutrient losses for all nine fields (43.7 ha) are estimated to be in total 5.52 kg of P, 373.64 kg of N and 752.08 kg of K. The losses result in costs for fertilizer equivalents of in total ~832.92 € for the period 2018–2020, from which K (66.3%) and N-fertilizer (28.3%) account for the most losses while costs for P-fertilizer are lowest (5.4%) based on comparable low fertilizer equivalents.

Based on the listed nutrient losses shown in Table 6, SLCH invokes an average economic cost of fertilizer equivalents of ~19.06 € ha^{-1} harvest^{-1} for the period 2018–2020. For the period 2021–2023, the increased unit prices of fertilizers strongly increase costs by ~93.2% to an average of ~36.82 € ha^{-1} harvest^{-1}. Especially increased prices of urea (130.4%) in 2021–2023 contribute to strong increases in costs of N-fertilizer equivalents. Considering maximum values for $SLCH_{crop}$ in the period 2021–2023, fertilizer costs of N, P and K can reach 111.08 € ha^{-1} harvest^{-1}, which can be reduced to 2.18 € ha^{-1} harvest^{-1} when minimal rates of $SLCH_{crop}$ can be achieved. In addition to the nutrient losses of N, P and K, in total 763.99 kg of Ca (in average 17.48 ±38.98 kg ha^{-1} harvest^{-1}) and 3476.34 kg of SOC (79.55 ±95.76 kg ha^{-1} harvest^{-1}) were removed from the topsoil during the harvest process, which are not considered in the cost calculations above.

4. Discussion

4.1. Rates and variability of SLCH for sugar beets

For the three years studied, the mean $SLCH_{crop}$ was at 5.7 Mg ha^{-1} harvest^{-1}. This mean soil loss is considerably higher compared to former studies which measured SLCH for sugar beets by machinery harvest in the field. Ruysschaert et al. (2007b) reported a $SLCH_{crop}$ of 3.6 Mg ha^{-1} harvest^{-1} (-37.8%), Faraji et al. (2017) of 2.26 Mg ha^{-1} harvest^{-1} (-60.4%) and Parlak et al. (2021) of 1.63 Mg ha^{-1} harvest^{-1} (-71.4%). However, for single fields, Ruysschaert et al. (2007b) found a maximum for $SLCH_{crop}$ of 30.1 Mg ha^{-1} harvest^{-1} which was ~42.65% higher than the maximum measured in this study (21.1 Mg ha^{-1} harvest^{-1}). In contrast, the minimum value of $SLCH_{crop}$ was 64.3% lower in this study (0.25 Mg ha^{-1} harvest^{-1}) compared to Ruysschaert et al. (2007b) (0.7

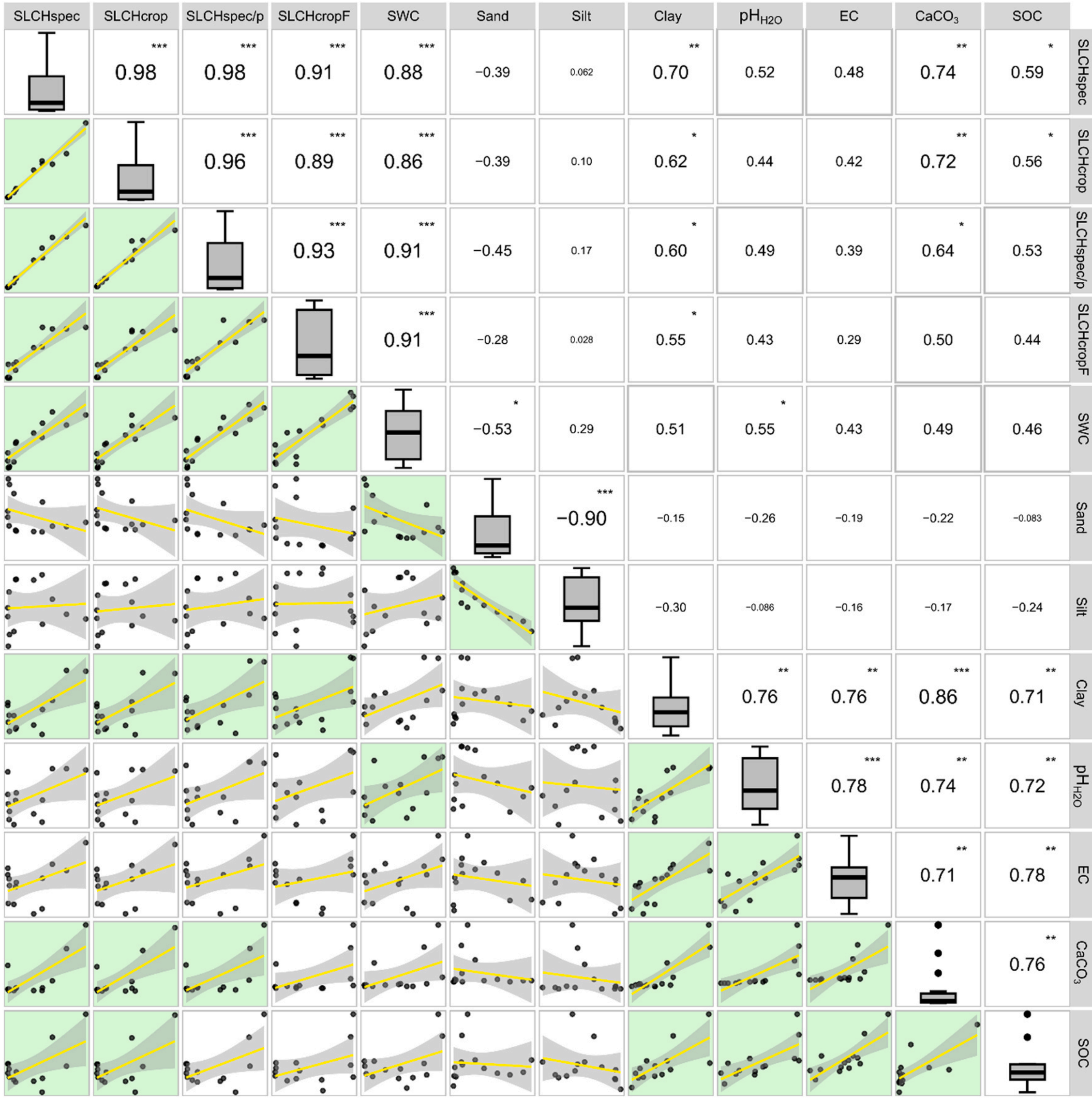

Fig. 6. Pearson correlation coefficients and linear Regression for SLCH values and soil properties.

Table 4
Regression equations and model fit for the best single model. Based on linear and non-linear transformations of significant ($p < 0.5$) independent variables.

SLCH	Variable	Formula	Adj. R^2	NSE	RMSE	MAE	Regression
spec	SWC	$y = -0.084 + 0.0078\,x$	0.67	0.67	0.039	0.033	Linear
	clay	$y = 0.064 + 0.174\,x + 0.104\,x^2$	0.44	0.40	0.052	0.047	Quadratic
	$CaCO_3$	$y = 0.035 + 0.364\,x$	0.43	0.43	0.051	0.044	Linear
	EC	$y = 0.064 + 0.119\,x + 0.145\,x^2$	0.43	0.19	0.060	0.049	Quadratic
	SOC	$y = 0.064 + 0.149\,x + 0.11\,x^2$	0.40	0.21	0.060	0.050	Quadratic
crop	SWC	$y = -7.54 + 0.7\,x$	0.61	0.61	3.82	2.97	Linear
	SOC	$y = 5.7 + 12.75\,x + 12.75\,x^2$	0.51	0.43	4.61	3.92	Quadratic
	EC	$y = 5.7 + 9.63\,x + 15.13\,x^2$	0.50	0.42	4.66	3.85	Quadratic
	$CaCO_3$	$y = 5.7 + 16.37\,x + 5.98\,x^2$	0.42	0.22	5.37	4.84	Quadratic
	clay	$y = 5.7 + 14.1\,x + 10.21\,x^2$	0.27	0.16	5.58	4.96	Quadratic
spec/p	SWC	$y = -98.11 + 9.04\,x$	0.78	0.77	35.35	31.54	Linear
	SOC	$y = 72.2 + 147\,x + 121.7\,x^2 - 90.1\,x^3$	0.45	0.42	56.67	43.28	Cubic
	$CaCO_3$	$y = 45.35 + 346.75\,x$	0.27	0.27	63.61	54.87	Linear
	clay	$y = 72.7 + 167.7\,x + 110.2\,x^2$	0.27	0.20	66.54	57.79	Quadratic
	SCB	$y = -1389.41 + 237.32\,\log(x)$	0.21	0.19	66.93	54.15	Logarithmic

Mg ha^{-1} $harvest^{-1}$), while there is no information on the range of measured SLCH by other studies.

The reason for the variability of $SLCH_{crop}$ between the different studies can be attributed to differing environmental (e.g. climate, soil) and soil management conditions which are known to have a big impact on the amount of SLCH on the one hand (cf. Section 4.2). On the other an

Table 5
Best performing equations and model indicators using all and only soil co-variables for $SLCH_{spec}$,$SLCH_{crop}$ and $SLCH_{spec/p}$.

SLCH	Variables	Formula	Adj. R^2	NSE	RMSE	MAE
spec	all	y = 0.051+0.131 SWC+0.063 SWC^2+0.148 clay+0.098 $clay^2$-0.051 yield+0.014 $yield^2$+0.002 legginess-0.126 $CaCO_3$	0.99	0.99	0.008	0.006
	soil	y = 0.064+0.158 SWC+0.072 SWC^2+0.105 clay+0.062 $clay^2$-0.046 SOC+0.050 SOC^2	0.89	0.88	0.023	0.018
crop	all	y = 5.05+8.64 SWC+8.06 SWC^2+11.84 clay+4.37 $clay^2$+8.71 yield+3.22 $yield^2$-3.19 SOC+3.58 SOC^2+0.05 legginess	0.98	0.97	1.07	0.79
	soil	y = 5.7+12.95 SWC+4.89 SWC^2+7.83 clay+4.45 $clay^2$-1.96 SOC+7.84 SOC^2	0.75	0.74	3.07	2.51
spec/p	all	y = 113.5+200.9 SWC+42.5 SWC^2+43.4 clay+86.4 $clay^2$+26.9 legginess-0.001 crop density	0.94	0.94	18.0	14.3
	soil	y = 72.7+218.7 SWC+55.2 SWC^2+35.9 clay+80.0 $clay^2$	0.87	0.87	27.07	20.29

Table 6
Nutrient losses and economic costs of fertilizer equivalents based on average fertilizer costs for the periods 2018–2020 and 2021–2023 for the nine investigated fields (43.7 ha).

	nutrient	mean	SD	min	med	max
nutrient losses(kg ha^{-1} $harvest^{-1}$)	N	8.55	±10.35	0.45	3.42	30.99
	P	0.61	±0.71	0.042	0.35	2.07
	K	17.21	±16.7	1.07	8.22	46.07
fertilizer costs2018–2020(€ ha^{-1} $harvest^{-1}$)	N	5.4	±6.53	0.28	2.16	19.58
	P	1.03	±1.19	0.07	0.58	3.47
	K	12.63	±12.25	0.78	6.03	33.8
fertilizer costs2021–2023(€ ha^{-1} $harvest^{-1}$)	N	12.54	±15.16	0.66	5.2	45.43
	P	1.97	±2.28	0.13	1.11	6.64
	K	22.31	±21.66	1.39	10.65	59.73

*The properties for each single sampling site are given in the supplementary (Table A1).

important factor in the variability can be linked to the sampling technique and harvesting process conducted in the individual studies. For example, Ruysschaert et al. (2007b) used a small, specially designed harvester pulled by a tractor which produced less soil tare due to additional cleaning systems. This harvester does not represent typical harvest machinery in mechanized agriculture, which may explain the lower average $SLCH_{crop}$ values. In addition, Faraji et al. (2017) and Parlak et al. (2021) collected manual samples of sugar beets after their uplift through the harvester with no accurate description at which step during the harvest process samples were taken. This also might lead to lower SLCH values when compared to sugar beets collected during the unloading process of the harvester as shown here.

Analysis of the harvests throughout the single years reveal considerable differences in SLCH. Especially $SLCH_{spec}$ between 2018 (0.013 ± 0.011 Mg Mg^{-1}) and the other two years (2019: 0.123 ± 0.046 Mg Mg^{-1}, 2020: 0.089 ± 0.085 Mg Mg^{-1}). 2018 was one of the driest years since instrument measurement (Schuldt et al., 2020; Zscheischler and Fischer, 2020), with a total average precipitation sum until harvest date of 344.3 mm for the investigated sampling sites, resulting in minimum values for SWC (14.2 ± 4.4%). In comparison, 2019 and 2020 had average total precipitation sums until harvest of 556.6 mm and 540.5 mm, respectively, which is 59% more on average than in 2018. Accordingly, SWC contents of 26.8 ± 4.2 and 19.8 ± 9.1% were 89% and 39% higher than in 2018. Since SWC has a very high impact on SLCH (cf. Section 4.2), the relatively low amount of $SLCH_{spec}$ in 2018 is likely to be a result of the overall dryness of the soil.

We also showed noticeable variations of SLCH for samples which were on the same field, e.g 9.6 and 21.1 Mg ha^{-1} $harvest^{-1}$ for field 8 (Table A1), which can be mainly explained by the variability of soil properties (e.g. clay, SWC; cf. Section 4.2). It is important to note that these differences are not accounted for by data from sugar factories, which only give single values for entire fields (e.g. 6.46 Mg ha^{-1} $harvest^{-1}$ for field 8). This indicates that SLCH provided by sugar beet factory data, are likely to fail in indicating the spatial variabilities within fields, which however is an important information in order to implement effective mitigation measures at field-level.

In addition to the few studies that have measured SLCH by machinery harvest of sugar beet in the field, there are nine studies that have considered SLCH data based on estimates by the sugar beet factories, including this study (Table 7). Based on these studies mean $SLCH_{cropF}$ ranges from 3.3 Mg ha^{-1} $harvest^{-1}$ (Schulze-Lammers and Strätz, 2003) to 13.8 Mg ha^{-1} $harvest^{-1}$ (Ruysschaert et al., 2005). In comparison our study showed an average $SLCH_{cropF}$ amount of 3.11 Mg ha^{-1} $harvest^{-1}$, which is the lowest of all former studies (Table 7). Therefore, this study enables for the first time to compare field-measured and factory-based SLCH for the same fields, which reveals that $SLCH_{cropF}$ only accounts for in average ~45.4% of the $SLCH_{crop}$ measured in our field experiments. This discrepancy is likely to be attributed to loading, transport and post-harvest cleaning which can considerably change soil tare between the time of harvest and measurements of the sugar beet factory (Schulze-Lammers and Strätz, 2003; Tuğrul et al., 2012). For example, in most cases the sugar beets are unloaded at beet clamps at the field border or at the headlands and stored there for later processing. In our study, we collected the sugar beets directly from the harvester during the unloading process (Fig. 3b) as stated in chapter 3.2.3. Consequently, our data reflects the soil loss by the harvester, which occurs over the entire field, but not include soil material which reaccumulates during and after the unloading of sugar beets at the beet clamp. Additionally, sugar beets can be stored at the beet clamp from a few days to several weeks (Kenter and Hoffmann, 2009). During this time the sugar beets are exposed to weather impacts (e.g. rain, solar radiation, wind), which can also loosen and detach some of the adhering soil material. For final transportation, the sugar beets are reloaded from the beet clamp to a truck by a beet cleaner loader ("Maus"). Latter introduces a further cleaning process to the harvested sugar beets, which causes that some percentage of the adherent soil re-accumulates at the beet clamp. The extent of reaccumulating soil is largely dependent on the condition of the adherent soil material (e.g. dry or moist) at the time of the reloading process and the cleaning efficiency of the used beet cleaner loader. Although we expect that the amount of soil which reaccumulates is rather low amount, it can be expected that SLCH of harvester, measured in this study, is slightly overestimating the soil loss which is entirely removed from the arable fields. In contrast, our approach delivers SLCH rates which affect the predominant part of the field (accept for the beet clamp ~1% area), which is important for sediment and nutrient budgets. If samples would have been taken after the unloading of the beet cleaner loader or for example from the sugar beet factory, no direct relation

Table 7
Rates of $SLCH_{crop}$ for sugar beets (according to Kuhwald et al., 2022, p. 5).

Reference	Soil loss(Mg ha^{-1} harvest^{-1})	Region/Country	Soil texture class	Year/period
(i) Machinery harvest				
Ruysschaert et al., (2007b), p. 1403	3.6 (0.7–30.1)	Belgium	sandy loam, loam, clay loam, silt loam, silty clay loam	2002–2004
Faraji et al., (2017), p. 5	2.26 (n.i.)	Iran	texture %	n.a.
Parlak et al., (2021), p. 4	1.63 (n.i.)	Turkey	clay loam, clay, sandy clay loam, sandy loam	2019
This study	5.7 (0.25–21.1)	Germany	sandy loam, clay loam, silty loam, silty clay, clay silt	2018–2020
(ii) Manual harvest				
Li et al., (2006), p. 1007	1.0 (0.2–1.9)	China	loam, silt loam, silty clay loam	2002
(iii) Factory data/modelled				
Poesen et al., (2001), p. 42	8.72 (4.37–19.52)	Belgium	n.a.	1968–1996
Ruysschaert et al., (2005), p. 323	8.8 (4.4–19.5)9.3 (4.7–19.4)	Belgium (regional)	many	1968–20001978–2000
Ruysschaert et al., (2005), p. 323	6.2 (3.4–13.4)5.9 (3.4–9.8)	Netherlands(regional)	many	1972–20011978–2000
Ruysschaert et al., (2005), p. 323	13.8 (7.7–20.5)	France (regional)	many	1978–2000
Ruysschaert et al., (2005), p. 323	6.9 (3.7–11.1)	Germany (West Germany; regional)	many	1977–1989
Ruysschaert et al., (2005), p. 323	5.0 (2.0–9.5)	Germany (East Germany; regional)	many	1959–1989
Ruysschaert et al., (2005), p. 323	5.2 (2.2–10.7)3.7 (2.2–5.5)	Germany (regional)	many	1978–20001990–2000
Ruysschaert et al., (2008), p. 221	10.0 (n.a.)	Belgium (regional)	many	1996–2004
Ruysschaert et al., (2008), p. 221	4.5 (n.a.)	Netherlands (regional)	many	1996–2004
Schulze-Lammers and Strätz, (2003) pp. 126–127	6.6 (n.a.)3.3 (n.a.)	Germany	n.a.	19902000
Tuğrul et al., (2012), p. 75	3.66 (n.a.)3.86 (n.a.)	Turkey (one factory) Turkey (regional)	n.a.n.a.	n.a.2008
Oztas et al. (2002), p. 236	3.4 (n.a.)	Turkey (regional)	n.a.	n.a.
Panagos et al., (2019), p. 495	5.66 (3.57–8.36)4.98 (1.95–8.36) 4.99 (1.95–7.88)	EU-15[a]EU-28[b]EU-28[b]	many	1975–19861987–19992000–2016
Parlak et al., (2008), p. 285	5.22 (n.a.)	Turkey (regional)	many	2005
This study	3.11 (0.48–6.46)	Germany	sandy loam, clay loam, silty loam, silty clay, clay silt	2018–2020

between sampled sugar beets and harvested area could have been taken, which can strongly bias the results especially in fields with heterogenous soil conditions. As we used samples during the unloading process we were able to relate calculated SLCH values to the insitu crop and soil conditions where they were harvested, allowing direct and less biased relations in the regression analysis. However, the differences between field- and factory-measured SLCH values imply that it is important to take caution when working with factory data, but also to clearly state at which specific step during harvest process samples are taken for measurements.

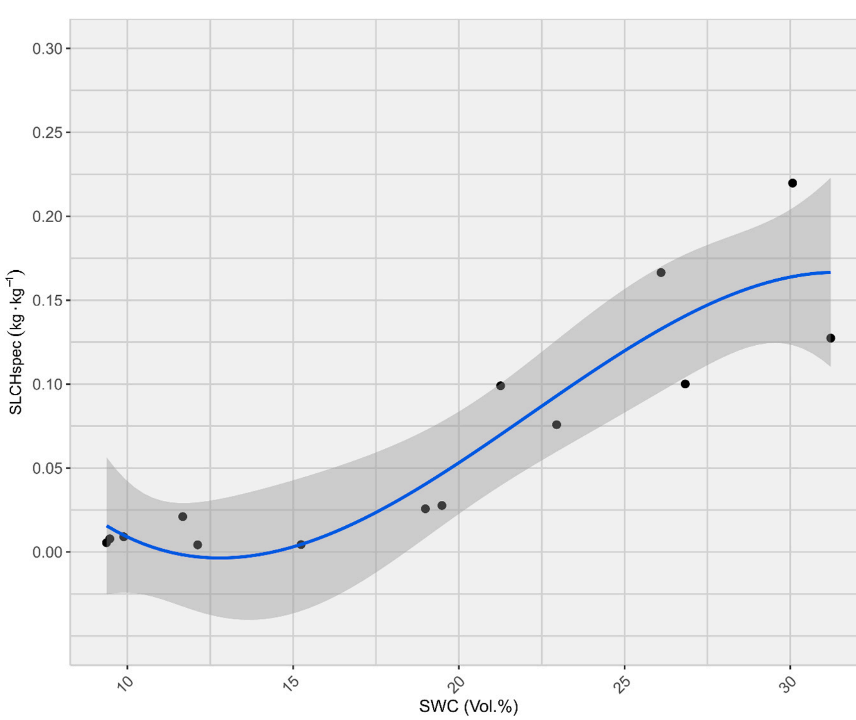

Fig. 7. Fitted non-linear regression line between $SLCH_{spec}$ and gravimetric soil water content (SWC) for all 14 sampling sites.

4.2. Effects of soil and crop properties

Similar to previous studies on SLCH by sugar beet harvest (e.g. Parlak et al., 2021; Ruysschaert et al., 2007a), we identified SWC as the most important parameter controlling SLCH. Although the best correlation of SWC was achieved with linear regression, we agree with former studies (Ruysschaert et al., 2007b; Ruysschaert et al., 2004) that SWC is more likely to have a non-linear (e.g. exponential, cubic) impact as illustrated in Fig. 7 on SLCH for several reasons: First, the fit of the exponential relation on SLCH respectively was only marginal weaker than the linear one, which can be neglected based on the small sampling size of 14 samples (13 due to LOOCV). Second, SWC was found having an exponential impact in all multiple regression models (Table 5).

The non-linear impact of SWC becomes even more apparent when splitting the dataset used in Fig. 7 into a subset of low SWC (9.3–15.2%; n=6) indicating dry soil conditions and of high SWC (19.0–31.2%; n=8) for rather moist soil conditions. For the dryer soil samples Fig. 8 demonstrates that SWC does not have a significant impact on SLCH, while for the moist samples (Fig. 8) a strong positive relationship between SWC and SLCH can be shown. Additionally, it seems that not only SWC but also other soil parameters have a varying impact on SLCH under different soil moisture conditions. For example, under dry soil conditions, none of the most important variables has a significant correlation with SLCH. Only SOC shows a negative moderate correlation which might indicate that a decrease of SOC increase SLCH in dry soils. Under moist soil conditions, the impact of SWC but also of clay and $CaCO_3$ becomes significantly stronger and in case of SOC turns into a positive relationship. The changing effect of SWC also explains the results of

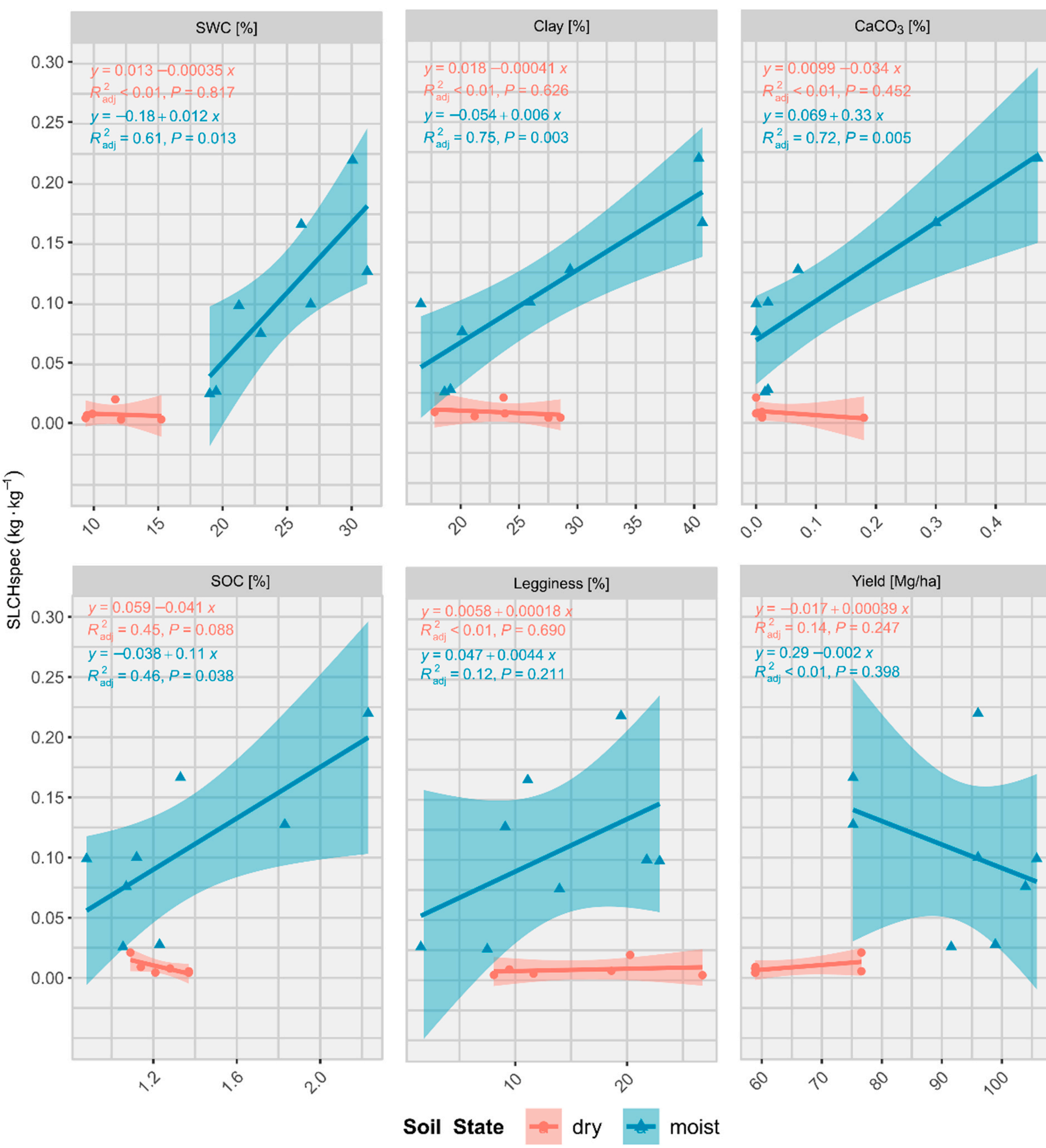

Fig. 8. Single linear regression of most relevant soil properties for $SLCH_{crop}$ for dry soil conditions (SWC < 17.5%; n = 6) and wet soil conditions (SWC > 17.5%; n = 8).

Faraji et al. (2017), who found a non-significant negative correlation between SWC and SLCH for soils with an average SWC of 16% (12.3–26.8%), representing rather dry soil conditions. Our results therefore suggest the occurrence of a tipping point for SWC at which SLCH increases strongly. According to our measurements this point is located around a SWC of 17.5% (15.2–21.3%), which also corresponds well to other studies (e.g. Ruysschaert et al., 2004, Ruysschaert et al., 2007a)

In addition to the strong influence of SWC as controlling variable, we also found that the clay content has a high impact on SLCH (Table 4). This also agrees with Ruysschaert et al. (2007b) who stated that clay content and SWC can explain most of the variation in soil loss due to sugar beet harvest (74%). However, other studies found quite lower correlations with clay but a stronger impact of sand or silt (Li et al., 2006; Parlak et al., 2021). Li et al. (2006) indicated an even negative relation ($R^2 = -0.64$) between clay and SLCH for manually harvested sugar beets. Regardless the harvesting technique we presume that the deviating results may be attributed to the smaller range of clay contents (24–37.6%), compared to the clay contents of our study (16.6–40.7%). Additionally, the study of Li et al. (2006) indicated a low range of SWC and rather dry soil conditions (average SWC = ~16%) than in our study (average SWC = ~19%), with much more samples lying underneath the expected threshold discussed above. This also underlines that clay content might influence SLCH differently under dry soil conditions and might slightly reduce SLCH to a specific threshold (Fig. 8).

Another novelty of this study was to assess the impact of EC, pH and $CaCO_3$ on SLCH. In addition to SWC, clay and SOC content it was found that these properties are also tightly positively related to SLCH. Accordingly, $CaCO_3$ contributed to the best performing regression model for $SLCH_{spec}$ (Table 5). Our data also showed for crop related properties that sugar beet yield and SC_B performed best in the correlation analysis, while in the multiple regression crop yield, crop density and legginess were identified to improve multiple regression predictions of SLCH. The importance of crop yield and density on SLCH was also shown in other studies (e.g. Parlak et al., 2021; Ruysschaert et al., 2007b), however this is the first study showing that legginess might be an important indicator to consider.

Nonetheless, we assume that the results as stated above indicate that factors which increase bonding of soil components and sugar beets will consequently lead to an increase in SLCH. This explains especially the correlation of clay, SWC and SOC. We also believe that the dependence of clay might also be related to the type and layers of clay minerals present in the region (e.g. 1:1 or 2:1 clay minerals). In this study region, for instance, multi-layered clay minerals such as illite or smectite are dominant (Ito and Wagai, 2017), which are more prone to swelling under moist soil conditions and promote aggregation (Blume et al., 2016b). This could increase soil adhering to the crops and be one reason for the shown effects of clay on SLCH in moist soils. Additionally, a possible explanation for the effect of pH and $CaCO_3$ content on SLCH is that both are indicators for the percentage and concentration of exchangeable Ca^{2+} in the soil. High percentages and concentrations of exchangeable Ca^{2+} can promote the aggregation of the soil (Blume et al., 2016a), which adversely might improve the bonding of soil to the crop and finally lead to increased SLCH.

4.3. Amounts and variability of nutrient losses and fertilizer costs

Based on the estimated losses of nutrients the average costs from fertilizer equivalents of 19.06–36.82 € ha^{-1} $harvest^{-1}$ (based on the time period) are much higher compared to similar studies. For example, based on a current exchange rate of 0.94 € $\$^{-1}$ Faraji et al. (2017) reported average costs of fertilizer equivalents of 1.48 € ha^{-1} $harvest^{-1}$ based on 3.35 kg N, 0.02 kg P and 1.74 kg K ha^{-1} $harvest^{-1}$ for Iran while Parlak et al. (2021) reported costs of 2.68 € ha^{-1} $harvest^{-1}$ for Turkey (N=1.84, P=0.02 kg K=0.91 kg ha^{-1} $harvest^{-1}$). The higher estimated costs in this study can be linked to three reasons: i) higher average $SLCH_{crop}$ rates of up to 3.5 time, ii) generally more fertile topsoil with especially higher P (up to 11.3 times) and K (up to 5.4 times) concentrations and iii) increases in fertilizer costs. In general contribution of P costs in the study area was lowest, based on low concentrations of P compared to K and N, while assumed fertilizes provided relatively high concentrations for P while prices were in the same order of magnitude, which was also stated by several other studies (e.g. Parlak and Blanco-Canqui, 2015; Parlak et al., 2018). We also showed that unit prices of fertilizers can be subject to high fluctuations which can have a very important impact on the costs of fertilizer equivalents induced by SLCH.

Based on the calculated costs, 0.38% (2018–2020) and 0.73% (2021–2023) of the revenue estimated from the yield (92 Mg ha^{-1} $harvest^{-1}$ and current sugar beet prices of 55 € Mg^{-1}) would need to be reinvested in fertilizers in order to return lost nutrients to the topsoil. However, harvesting under unfavourable soil conditions (e.g. wet soils) can increase the proportion of fertilizer costs to 2.21% of the revenue when maximum SLCH rates are taken and high fertilizer costs are assumed (2021–2023).

When using the average cultivated sugar beet area of Germany since 2018 which is in average ~4298 $km^2 \cdot year^{-1}$ (Crop type maps; Blickensdörfer et al., 2022; Schwieder et al., 2023) and taking estimated fertilizer costs, SLCH would invoke costs for fertilizer equivalents of N, P and K of roughly ~12 Mil. $€ \cdot year^{-1}$ for Germany. In addition, 34,384 Mg SOC $year^{-1}$ would be removed from arable soils during sugar beet harvest by the harvesting machine. It is important to state, that these rough calculations on economic costs are based on 14 sampling sites in one study region and take only into account the restoration of N, P and K after harvest. Accordingly costs of other damages which might be induced by SLCH are not considered. For example, it is yet difficult to determine the economic value of SOC or the mineral soil phase itself on soil fertility. However, a recent study by Ma et al. (2023) showed that sequestration of SOC can be one-fifth as effective as N-fertilization for improving crop yield. Thus, the total economic cost to restore full soil fertility after sugar beet harvest can be expected to be even higher than the estimates given here based on N, P and K.

4.4. Limitations, future advances and research needs

Although this study reveals important new findings in SLCH research, there are some limitations that should be addressed. As mentioned in Section 4.2 one limitation in this study can be linked to the sampling size which to some extent limits the statistical interpretability. Another difficulty arises from multicollinearities among some of the explanatory variables for SLCH. Although this was considered in the regression analysis and equations, it is difficult to determine the independent impact of each variable due to the wide range of crop and soil properties and the small number of sampling sites. However, as each sample is based on a root average of ~169 sugar beets, the samples are expected to show robust values well representing each of the sampling site.

Another uncertainty in the results are the different sugar beet varieties used within the study. In total three different sugar beet varieties from the company KWS SAAT were seeded (2018: LISANNA, 2019: ANNAROSA, 2020: LUNELLA) based on expected highest sugar yield by the farmer. As the type of variety can also have an impact on SLCH (Ruysschaert et al., 2007b) it is also likely that differences in variety such as root hairs and morphology differ among crop years, although the effect is expected to be relatively low. Moreover, variabilities in SLCH values can also be expected from different machinery and machine settings during the harvest. In total three different harvesting machines from two different brands were used (GRIMME and ROPA). Although cleaning techniques do not show large differences (e.g. mulder, sieving stars), technical differences can be expected in the adaptation of driving speed of the harvester and speed on which sieving stars operate. The speed during the harvest is usually optimized based on soil conditions (e.

g. soil texture and SWC).

Sugar beets in this study were grown after winter fallow which means that no cover crops were seeded before sugar beets. However, the pre-management in case of cover crop or fallow but also cropping systems in general is likely to have an impact on the soil conditions and crop growth, which might affect SLCH. Additionally, we only investigated fields which were tilled by chisel plough. However, the effects of different tillage and farming systems (e.g. ploughing, no-till, organic farming) on SLCH are yet rarely considered in current literature. Furthermore, it was shown that SLCH-values can differ strongly within fields. Therefore, it would be interesting to analyse in more detail the parts of the field where different soil properties are expected. A typical example is the difference between headlands and the core field, which usually shows different degrees of soil compaction (Augustin et al., 2020).

In addition, it seems necessary for future research to focus on the way root crops are collected, cleaned and analysed. Current studies show a different methodology of deriving SLCH hampering the comparability of results. To understand the full process and dynamic of SLCH, data on SLCH at the unloading of the harvester (this study) and before and after the transfer of sugar beets by the beet cleaner loader is urgently needed in addition to data of the sugar beet factories.

Finally, the results show that SLCH of sugar beets can have a major contribution to soil erosion, SOC and nutrient losses, resulting in fertility losses that lead to high direct costs for farmers. In particular, the spatio-temporal variability of SLCH rates necessitates a comprehensive assessment of SLCH at larger scales (e.g. national or pan-European scale). New advances in spatially explicit derivation of crop rotations and soil moisture conditions using satellite data and machine learning (e.g. Blickensdörfer et al., 2022, O et al., 2022) could support the spatial prediction and impact of SLCH at larger scales and over longer temporal extents. This is necessary not only to develop conservation measures and derive policies to mitigate SLCH, but also to advise farmers on the risk of soil and nutrient losses and fertiliser reinvestment that may accompany SLCH.

5. Conclusions

This study indicated that soil loss due to sugar beet harvest in highly mechanized agricultural areas can lead to considerable soil losses, which may exceed soil formation rates by far. We showed that average SLCH measured in our study is noticeably higher than in comparable international studies and also than estimates provided by sugar beet factories. We also showed that SLCH can not only cause significant losses of mineral soil, but of SOC and nutrients (N, P and K) during the harvest process, which not only contributes to ongoing soil degradation and a reduction of soil health but also causes direct costs for farmers.

Thus, we developed new regression models to estimate SLCH based on easily available soil and crop data (e.g. SWC, clay, yield). The study also confirms the overall importance of SWC on SLCH, suggesting that SWC also influences the contribution of other soil properties on SLCH. We could also demonstrate that SLCH values can have strong variabilities among different years but also within single fields, while the impact of multiple variables still needs to be assessed (e.g. crop sequences, tillage practices, machine parameter and locally adapted adjustments during the harvest).

Based on the differences between measured SLCH from the harvester during the unloading and SLCH based sugar beet factory data we also conclude that additional measurements of SLCH immediately before and after sugar beet transfer by beet cleaner loaders are needed to increase knowledge on the full SLCH process and to determine quantities of the adhering soil which reaccumulates leaving the field. This would be a huge advantage to create reliable models and design measures to reduce SLCH and consequently to restore soil health for sustainable agriculture.

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CRediT authorship contribution statement

Rainer Duttmann: Writing – review & editing, Supervision, Resources. **Michael Kuhwald:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Fritjof Busche:** Writing – review & editing, Visualization, Methodology, Data curation. **Joachim Brunotte:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Philipp Saggau:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

Data Availability

Data will be made available on request.

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Appendix A

Figure A1. Cleaning of the sugar beets. (a) cleaning devices; (b) Soil-water-suspension in glasses placed in the oven to dry; Glass after drying.

Table A1
Measured properties and estimated SLCH of all sampling sites.

FID	SID	$SLCH_{spec}$ [Mg Mg^{-1}]	$SLCH_{crop}$ [Mg ha^{-1}]	$SLCH_{spec/p}$ [g p^{-1}]	$SLCH_{cropF}$ [Mg ha^{-1}]	SWC [%]	sand [%]	silt [%]	clay [%]	yield [Mg]	SC_B [cm^2 p^{-1}]	Leg. [%]	crop weight [g]	SOC [%]	pH_{H2O} [-]	EC [µs cm^{-1}]	N [%]	P_2O_5 [mg kg^{-1}]
1	1	0.028	2.73	33.9	2.34	19.5	3.0	77.8	19.1	98.9	550.9	1.5	1224.9	1.2	7.5	191.3	0.1	289.9
2	2	0.009	0.53	6.0	0.48	9.9	45.0	37.2	17.8	58.9	373.0	9.5	666.6	1.1	7.2	180.5	0.1	296.6
2	3	0.004	0.26	3.0	0.48	15.2	21.0	50.5	28.6	58.9	378.5	8.1	681.5	1.2	7.5	241.0	0.1	389.1
3	4	0.004	0.25	2.3	0.54	12.1	15.5	57.0	27.5	58.9	321.4	26.8	531.4	1.4	7.8	218.0	0.2	297.7
3	5	0.008	0.46	6.0	0.54	9.5	7.7	68.5	23.8	58.9	406.2	18.6	758.8	1.3	7.1	204.0	0.1	252.9
4	6	0.026	2.35	33.4	1.40	19.0	3.7	77.7	18.6	91.6	570.3	7.5	1299.4	1.1	7.4	175.8	0.1	281.6
5	7	0.166	12.51	177.8	6.27	26.1	7.1	52.2	40.7	75.2	506.6	11.1	1068.0	1.3	7.9	233.0	0.1	504.6
5	8	0.127	9.58	175.4	6.27	31.2	7.4	63.2	29.4	75.2	589.4	9.1	1376.4	1.8	7.9	255.0	0.2	328.8
6	9	0.076	7.88	96.1	4.05	23.0	2.6	77.3	20.1	103.9	562.1	14.0	1267.6	1.1	7.2	81.7	0.1	222.3
7	10	0.021	1.61	19.3	2.09	11.7	36.8	39.5	23.7	76.6	460.2	20.3	918.4	1.1	7.0	114.7	0.1	207.3
7	11	0.006	0.42	4.9	2.09	9.4	50.1	28.8	21.2	76.6	450.2	11.6	888.0	1.4	7.3	117.8	0.1	424.8
8	12	0.220	21.1	216.8	6.46	30.1	10.9	48.8	40.4	96.0	481.7	19.5	986.3	2.2	7.9	330.0	0.2	255.5
8	13	0.100	9.6	104.9	6.46	26.8	29.2	44.9	26.0	96.0	500.6	21.8	1048.0	1.1	7.4	206.0	0.1	143.6
9	14	0.099	10.5	138.3	4.13	21.3	2.2	81.2	16.6	105.8	594.4	22.9	1397.3	0.9	7.0	99.0	0.1	79.9

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