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RESEARCH ARTICLE

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No relationship between outputs of simple humus balance calculators (VDLUFA and STAND) and soil organic carbon trends

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Abstract

Simple humus balance calculators were developed for farmers and consultants to determine the best crop rotation and amount of organic fertilizer required to improve soil quality and prevent nutrient leaching in croplands. Although the potential of these tools to infer the impact of different agricultural practices on soil organic carbon (SOC) dynamics in croplands is not well studied, they have been integrated in several farm-level climate or environmental impact assessment calculators. Here we examine the correlation between humus balance values estimated with two different tools developed in Germany/Central Europe and observed changes in SOC content at 14 long-term sites in Switzerland. The first tool was developed by the Association of German Agricultural Investigation and Research Institutes and is referred to as the VDLUFA. The humus balance calculator STAND is a descendent of the VDLUFA that accounts for pedoclimatic factors in Central Europe. Crop rotations were distinguished based on cultivation practice, whereby those with mixed fertilization were supplied with mineral fertilizer alone and in combination with organic materials, while those with organic fertilization include unfertilized and organic fertilizer treatments. An analysis of 133 short-term observations (i.e. individual crop rotations of five and 6-year duration) and 26 long-term observations (i.e. several crop rotations with a total duration of ≥10 years) showed that humus balance values (kg C ha^{-1} $year^{-1}$) of short-term crop rotations were not or only poorly correlated with the observed change in SOC content (%) ($R^2 = 0.06$ in STAND and $R^2 = 0.05$ in VDLUFA for crop rotations with organic fertilization, and $R^2 < 0.01$ for crop rotations with mixed fertilization). The correlation did not improve when the humus balance values of long-term observations with mixed fertilization were compared with decadal SOC development ($R^2 = 0.04$ for STAND and $R^2 = 0.06$ for the VDLUFA). Stronger correlations were found only for long-term observations with organic fertilization ($R^2 = 0.68$ for STAND and $R^2 = 0.64$ for the VDLUFA). These findings underline that while the studied humus balance calculators are able to distinguish the effect of different fertilizers (organic vs. mineral) on a farm's humus supply on the longer term, neither are suited for predicting SOC trends over single crop rotations. Although this study was carried out in Switzerland, the results should apply to any region with temperate climate and similar soil properties.

KEYWORDS

agricultural environmental assessment tools, organic amendments, soil carbon sequestration, soil organic matter

1 | INTRODUCTION

Highlights

- Humus balance values calculated over 5–6 years were not correlated with observed changes in SOC.
- Logical interpretations of humus supply evaluations do not always align with observed SOC trends.
- The two simple humus balance methods performed similarly at numerous sites.
- Simple humus balance methods are not suitable tools for assessing SOC development.

Mitigating climate change and achieving food security necessitates the identification and implementation of agricultural practices that build humus and ultimately promote soil carbon sequestration in arable environments (Griscom et al., 2017; Lal, 2011). Humus, or soil organic matter (SOM), is composed of plant and animal residues at different stages of decomposition. Since SOM contains approximately 50% carbon (Pribyl, 2010), the maintenance and enhancement of the soil's humus content is vital for the promotion of soil carbon sequestration, which is defined as a net atmospheric carbon dioxide (CO_2) reduction through a soil carbon increase (whereby organic carbon input is greater than organic carbon output in the specific soil) (Fuss et al., 2018; Smith, 2016). To estimate potential increases in carbon storage in arable soils, soil models of different complexity were integrated in farm-scale environmental impact assessment tools (Paustian et al., 2016). These soil models use empirical equations to relate regional climate, land use and farm management parameters (and other factors depending on the quality of available data) and evaluate changes in SOM or soil organic carbon (SOC) (Hani et al., 2003; Hillier et al., 2011; Paustian et al., 2017). This strategy helps to inform on the effects of agricultural practices on humus content or SOC stock over time and guides farmers in implementing climate protection measures.

As global interest to promote SOC storage in croplands increases due to their CO_2 removal potential, members of the public and private sectors have begun to provide financial incentives for farmers who increase soil carbon (Soussana et al., 2019; USDA, 2016). However, measuring humus buildup or carbon sequestration in arable soil is difficult due to high spatial and temporal variability and methodological challenges (Lal, 2018; Paustian et al., 2019; Smith et al., 2020). For example, direct measurements, remote sensing and soil modelling techniques are used in existing protocols to measure and monitor changes in SOC stock (Paul et al., 2023), and each offers unique advantages and disadvantages. Direct measurements methods are the most reliable, but on-site measurements can be expensive and time intensive, particularly for large areas. Remote sensing techniques are more cost-effective; however, the accuracy and applicability of remote sensing data at high spatial and temporal resolutions depend on specific environmental conditions and available resources. Soil models are also cost-effective and readily available to most users, but models range widely in their complexity and associated uncertainties. Carbon credits can be issued using one or a combination of these techniques, and soil models in particular are already in use by public and private certificate providers in Australia, Europe and the United States (Black et al., 2022; Oldfield et al., 2022; White et al., 2021).

Collectively, soil models are independent calculators that have been created to aid scientists, farmers, consultants, governmental agencies and other stakeholders assess the impact of agricultural practices on important parameters such as SOM and SOC (Heil et al., 2022; Kwiatkowska-Malina, 2018; Murindangabo et al., 2023).

Mechanistic SOC or ecosystem models such as the Rothamsted Carbon model (RothC), the Candy Carbon Balance model (CCB), the Introductory Carbon Balance Model (ICBM) and CENTURY are based on first-order kinetics that quantify change in soil carbon stock (Andrén & Kätterer, 1997; Coleman & Jenkinson, 1996; Franko et al., 2011; Parton et al., 1987). In comparison, humus balance calculators provide assessments of a farm's humus supply using comparatively simple methods. These tools aim to support sustainable agricultural practices and climate adaptation by evaluating the best crop rotation and organic fertilizer combinations required to maintain optimal soil function (Kolbe, 2010; Körschens et al., 2004).

As the aim of the mechanistic models and the simple humus balance methods differ, the application of each approach is dependent on their respective capabilities and limitations. Mechanistic models provide more accurate calculations of SOC stock, but they have a higher requirement for input data and technical expertise. This renders them nonviable for use by farmers and limits their application in farm and/or plot level assessments to instances in which sufficient data are available. Simple humus balance calculators do not have a high demand for site-specific data, and qualitative evaluations of the humus supply in agricultural plots can be determined without the use of a computer; however, quantitative assessments of humus content are beyond the scope of simple humus balance methods (Brock et al., 2013; Ebertseder et al., 2014). Overall, the effectiveness of commonly used mechanistic models and simple humus balance methods have been evaluated in a few scientific studies, and they were found to be satisfactory advisory tools for arable soils (Brock et al., 2012; Dechow et al., 2019; Franko et al., 2011; Kolbe, 2005).

The method developed by the Association of German Agricultural Investigation and Research Institutes (VDLUFA) and its 'standortangepasster' (STAND) or site-adjusted descendant are the most widely recognized humus balance models in Germany, Austria and Switzerland (Brock et al., 2013). These humus balancing approaches are derived from the 'natural soil potency' concept, whereby arable land use is divided into different categories that relate to the improvement or degradation of 'soil potency' (Feller et al., 2003). According to this principle, humus balance is defined as the difference between coefficients that represent the humus supply (the amount of humus added to the soil from organic fertilizers and crop residues) and the humus demand (the depletion of humus) of a crop rotation (Equation 1).

$$\text{humus balance} = \text{humus supply} - \text{humus demand} \quad (1)$$

The resulting humus balance is then assessed for the risk the agricultural practice poses to soil productivity and nutrient leaching (Kolbe, 2005, 2010). The same evaluation criteria are used for the VDLUFA and STAND humus balance models; however, differences in the parametrization of each method leads to particular strengths and weaknesses. For example, the VDLUFA humus balance calculator can be applied when site-specific factors are unknown because the model's humus reproduction coefficients are specified in accordance to the crop type and the material composition of the organic fertilizers (Körschens et al., 2004). However, this approach may not be suitable for sites with distinct attributes since all sites are treated equally within the model, as climatic and environmental factors are not considered. Conversely, STAND uses a site-adjusted approach in which the crop-related humus supply and demand coefficients are characterized based on the effect of five soil and climatic factors on SOM turnover (Kolbe, 2010). STAND also accounts for variations in the humus contributions of organic materials by adjusting the humus supply coefficients based on supply level (Kolbe, 2010). These improvements have led to the implication that STAND can better identify the impact of agricultural practices on SOM (Kolbe, 2007; Kolbe & Zimmer, 2015). However, it is difficult to apply STAND when the five defining site-specific parameters are unknown, or when one is uncertain about the material composition of the organic fertilizer additions.

The VDLUFA humus balance method has been verified using data from Central Europe including a site from Switzerland (Kolbe, 2005). However, the validity of VDLUFA for Switzerland is somewhat uncertain because the tool was developed using data from Eastern Germany where precipitation rates are lower than in Southern Germany and Switzerland (https://www.dwd.de/DE/klimaumwelt/klimaatlas/klimaatlas_node.html). STAND, however, is clearly stated as a tool to be applied in Central Europe. Nonetheless, a controversial shortcoming of the VDLUFA and STAND humus balance calculators is that the evaluation criteria employed by both models to interpret a farm's humus supply has not been validated (Brock et al., 2013). This indicates a need to examine the extent to which the VDLUFA and STAND humus balance outputs can infer changes in SOM and/or SOC content for a range of agricultural practices.

Simple humus balance calculators, specifically the VDLUFA and STAND, are the focus of this study because they have been integrated into environmental impact assessment tools that perform farm-level evaluations of greenhouse gas (GHG) emissions and SOM change (Hani et al., 2003; Oberholzer et al., 2006). For example, the Swiss Agricultural Life Cycle Assessment Future

(SALCA-Future) tool (Nemecek et al., 2024) includes a development of the humus balance method developed by Neyroud et al. (1997) that integrates initial SOM content and a mineralization coefficient in its evaluation of the impacts of agricultural practices on soil quality (Oberholzer et al., 2006). The Arbeitsgruppe Berechnungsstandard für Einzelbetriebliche Klimabilanzen in der Landwirtschaft, which stands for the 'Calculation standard for single-farm climate balances in agriculture' tool (hereafter referred to as BEK) allows interested parties to conduct and compare GHG calculations at the farm-scale (Arbeitsgruppe BEK, 2021). Humus changes are evaluated within the BEK tool according to the VDLUFA humus balance model (Arbeitsgruppe BEK, 2021). The VDLUFA method is also included as a module in the Response-Inducing Sustainability Evaluation (RISE) tool which examines the economic, social and environmental sustainability performance of agricultural production at the farm level (Hani et al., 2003). Since its inception, RISE has been used on over 4500 farms in 60 countries (Thalmann et al., 2022). Similar to the humus balance methods themselves, these environmental impact assessment tools can be used by farmers (and not only scientists), which makes them further applicable in agroecological farming and builds on the empowerment of farmers and the co-creation of knowledge. However, to date, there is insufficient testing of the accuracy and practicality of the VDLUFA humus balance method, and it remains unclear if the site-adjusted STAND method outperforms the VLDUFA. Therefore, it is imperative that there is clarity about the limitations and potentials of these popular humus balance methods, and that this knowledge is widely available.

Here, we aim to assess the correlation between the humus balance values determined by the VDLUFA and STAND methods and observed changes in SOC content at 12 long-term soil monitoring sites (cropland) and two long-term experiments in Switzerland. We will also discuss (1) the extent to which these humus balance methods can inform on soil carbon changes and (2) the way forward with decision-support tools for climate smart farm management strategies.

2 | MATERIALS AND METHODS

2.1 | Description of sites, agricultural practices and soil organic carbon measurements

Farm management practices and soil organic carbon data were gathered from a total of 14 different sites in Switzerland: two long-term experimental cropland sites, DOK (D: biodynamic, O: bioorganic, K: conventional; Krause et al., 2022) and p24A (Maltas et al., 2018), and 12 long-term soil monitoring sites (on cropland) from the Swiss National Soil Monitoring Network (NABO; Gross et al., 2021; Gubler et al., 2022). The NABO sites are not experimental fields and are managed by independent farmers. As such, these sites represent agricultural management and soil development under practical conditions in Switzerland. Overall, the 14 sites represent a range of soil (soil clay content 5.8%–59.0%) and climate conditions in Switzerland (mean annual temperature 8.5–11.7°C and precipitation 840–1528 mm).

Precise descriptions of the two long-term field experiments (DOK and p24A) and the 12 NABO's sites and operations have been published in numerous works (see above). Briefly, the DOK experiment has a split-split-plot design with eight treatments and four replicate plots for each of the three subplots A, B and C, which represent different cultivated crops, while the p24A experiment has a split-plot experimental design with six main treatments and four replicates for each of the four subtreatments that represent different levels of mineral N-fertilization. The DOK and p24A experiments each consists of 96 experimental plots, which are 5 × 20 m at the DOK site and 4.5 × 20 m at the p24A long-term experimental site. In this study, we focused on the eight treatments in subplot A of the DOK experiment. The NABO monitoring sites each are represented by a 10 × 10 m sampling plot.

The examined crop rotation variants are representative of a range of agricultural practices in Switzerland. The length and composition of crop rotations and the type and amount of applied organic fertilizer varied among sites, and at some sites, between crop rotations over time. Table 1 summarizes the survey period, length of the short-term observations, site group categorization in the STAND model and the number of crop rotation variants examined in this study. Crop rotations were composed of different assemblages of cereal and oil crops (wheat, barley, triticale, rapeseed and sunflower), root crops (beetroot and potato), maize (silage and grain), grain legumes (soybean and protein pea) and temporary grasslands (grass-clover ley). In addition to the main crops, specialty crops (onion, strawberry and carrot) and secondary crops (intercrops) were cultivated in some crop rotations.

In this study, the agricultural cultivation practices are defined based on the use of mineral fertilizer. Crop rotations with organic fertilization are characterized as those that are either unfertilized or those that exclusively use organic materials, while crop rotations with mixed fertilization consist of mineral treatments that are applied alone and/or in combination with organic amendments.

TABLE 1 Brief description of the crop rotations at the 14 long-term sites examined in this study. More detailed information (e.g. crop types and organic amendment additions) is given in the main text.

Site name	Examined period	Length of crop rotations (years)	STAND site group classification	Number of crop rotation variants (*n*)
DOK	1982–2017	6	5	48
NABO 1	1986–2010	5	4	5
NABO 2	1989–2013	5	3	5
NABO 3	1985–2009	5	5	5
NABO 4	1988–2012	5	5	5
NABO 5	1988–2012	5	6	5
NABO 6	1988–2012	5	5	5
NABO 7	1988–2012	5	5	5
NABO 8	1988–2002	5	5	3
NABO 9	1986–2010	5	2	5
NABO 10	1988–2012	5	3	5
NABO 11	1986–2012	5	5	5
NABO 12	2000–2009	5	2	2
p24A	1976–2004	5 and 6	5	30

The p24A site consists of numerous organic fertilizer treatments, while the DOK site includes a mineral fertilizer treatment and multiple organic fertilizer treatments. All of the NABO sites use mineral and organic fertilizers, with cattle manure, cattle slurry and green manure being the most commonly applied organic amendments.

Sampling of the topsoil (0–20 cm) and SOC content measurements were determined differently at the long-term sites. At the DOK site, a composite sample was collected from 15 to 20 soil cores from each of four experimental plots per treatment following the annual crop harvest using a 3 cm diameter corer. Krause et al. (2022) reanalyzed the archived soil samples using a Vario Max Cube equipped with a thermal conductivity detector (Elementar Analysensysteme, DE), in which SOC was determined as the difference between total soil carbon and inorganic carbon determined in 1 g subsamples. At the p24A site, a composite sample of 10 cores (3 cm diameter) was collected from each of the six treatments after the wheat crop harvest every 6 years. Soil organic carbon was then measured according to the Swiss standard methods which involved a modified potassium dichromate oxidation procedure using hot sulfuric acid (FAL et al., 2011). At the NABO long-term soil monitoring sites, four composite soil samples were collected from 25 cores (2.5 cm diameter) each in 5-year intervals and archived. SOC analyses were performed on the four composite samples either by dry combustion with an elemental analyser (Elementar Analysensysteme, DE) or by wet oxidation and retitration of potassium dichromate (FAL, 1996). To allow comparison of the SOC results at the p24A and NABO sites, respectively, Keel et al. (2019) and Gubler et al. (2018) recalculated the results of the wet oxidation method to that of dry combustion method using site-specific conversion factors.

2.2 | Humus balance methods and outputs

The humus balance values of short-term (5 and 6 years in length, $n = 133$) and long-term (≥10 years in length, $n = 26$) observations were determined in Microsoft Excel based on the VDLUFA and STAND humus balance methods. Here, short-term observations refer to singular crop rotations and long-term observations represent all crop rotations of individual plots within the sampling period at a particular site. Both models consist of coefficients that represent the humus reproduction performance of different crops and organic materials. The humus balance value is calculated as the average of the humus reproduction coefficients of the cultivated crops and organic material applied during a crop rotation (Equation 2), and is measured in units of humus equivalents (Häq, which is equal to 580 kg humus-C, Körschens et al., 2004): where *C* represents the positive (humus supply in kg humus-C ha^{-1}) and/or negative (humus demand in kg humus-C ha^{-1}) coefficient of the crops cultivated in a crop rotation, *O* is the humus supply coefficient for organic material(s) applied during a crop rotation (in kg humus-C t^{-1}), I the input amount of organic amendment(s) (t ha^{-1}) and L the length of the crop rotation (in years). The humus balance values are expressed in kg humus-C ha^{-1} for an entire crop rotation.

$$\text{Humus balance value} = \frac{\left(\sum_{i=1}^{\text{crops}} C_i + \sum_{k=1}^{\substack{\text{Organic}\\ \text{amendments}}} O_k \times I_k\right)}{L}. \quad (2)$$

The VDLUFA outlines two sets of reference values for the humus coefficients of crops, the lower and upper values, which are applied based on the farm's cultivation practice and soil condition (Asmus & Herrmann, 1977; Leithold et al., 1997). The lower values are used in instances in which the crop rotations with mixed and organic fertilization are conducted on farms to maintain good soil condition and function, while the upper values are applied for soils in poor condition and for agricultural practices that have a high humus requirement (Table S1; Körschens et al., 2004). In the VDLUFA model, each set of crop-specific humus reproduction coefficients was derived based on assumptions of the estimated humus supply or consumption by the crop throughout its growth under average soil and climatic conditions, and the specific set of humus reproduction coefficients is applied to all areas. STAND builds upon the lower VDLUFA crop-specific humus reproduction coefficients and adjusts these values for different locations by incorporating the effects of five site-specific parameters on SOM formation (Table S1). These soil and climate parameters include soil type, soil fine fraction percentage, soil carbon to nitrogen (C/N) ratio, annual mean temperature and precipitation (Kolbe, 2010). The German soil textural classification system ('Bodenartendiagramm') serves as the foundation for the soil type and fine fraction percentage parameters. This system defines the particle size of silt and sand differently from the methods used at the long-term sites. Therefore, the locations for the long-term sites were determined based on soil C/N ratio, the two climate parameters and the clay specifications for soil type and fine fraction percentage. The 14 long-term sites represent five of the six site group categories in the STAND model.

The humus reproduction coefficients for organic amendments also differ between the VDLUFA and STAND humus balance models (Table S2). In the VDLUFA, these coefficients are specified based on the type and dry matter content of the organic material, while STAND adjusts the humus reproduction coefficient for organic amendments in accordance with the applied amount of the organic fertilizer (Kolbe, 2012). Within STAND, the humus coefficients for organic materials decrease as the fertilization amount increases (Kolbe, 2010).

It is important to note that although the humus equivalence unit for humus reproduction coefficients is usually converted into kilograms of humus carbon per hectare per year (kg humus-C ha^{-1} $year^{-1}$) as is done in this study, the VDLUFA and STAND humus balance methods do not have a quantitative link to soil humus stocks and therefore do not directly reflect changes in the SOM. For all crop rotations, the humus balances were calculated using the site-specific STAND values and the lower values of the VDLUFA method because crop rotations with both mixed and organic fertilization are applied to soil in good condition at the long-term sites examined in this study (Tables S1 and S2). The humus balance values were then compared with the change in SOC content in the topsoil (uppermost 20 cm of the soil) between the beginning and end of the crop rotation.

The VDLUFA- and STAND-derived humus balance values were assigned to one of five humus supply groups (A–E) which evaluates the sustainability of the crop rotation and fertilizer use (Kolbe, 2008; see Table S3 for an example of VDLUFA and STAND determinations). Humus supply groups A and B represent very low and low humus levels, respectively, which can harm soil productivity over time. This means that the amount of organic matter that is added to the soil either through the growth of humus building crops or the application of organic amendments is too low relative to the amount of organic matter that is removed from the soil throughout a crop rotation. Humus supply group C represents a balanced, or optimal humus supply, while groups D and E denote high and very high humus supply levels, which pose an increased risk for nutrient leaching. The thresholds of the humus supply groups differ based on the crop rotation's fertilization scheme (organic and mixed). Within each model, crop rotations in the organic fertilization category are defined based on absence of applied mineral fertilizer; this includes control treatments that do not receive any fertilizer. Conversely, crop rotations with mixed fertilization are characterized by the use of mineral fertilizer, either independently as solitary mineral fertilizer treatments or in combination with organic amendments.

2.3 | Data analysis

Statistical analyses and graphical representations were performed in R (R Core Team, 2022). The humus balance of short-term observations (i.e. single crop rotations of 5 or 6 years) and long-term observations (i.e. several crop rotations with a total duration of ≥10 years) were conducted separately. Soil organic carbon measurements for each year is represented as the mean of replicate treatment plots at the long-term experimental sites ($n = 8$, DOK; $n = 6$, p24A) and the mean of one to four composite samples collected at each of the 12 NABO monitoring sites ($n = 12$ for all of the NABO sites). We quantified standard errors of the SOC changes (SE_z) using Equation 3 to account for error propagation. The standard error of the first year of a 5- to 6-year rotation is denoted by SE_x and the last year by SE_y

$$SE_z = \sqrt{SE_x{}^2 + SE_y{}^2}. \tag{3}$$

Especially in the case of the NABO sites, we could not calculate standard errors for all rotations because, in several cases, only a single composite sample was available. We therefore decided not to show the error bars but present the errors in the Figure legend. A *t*-test was conducted to compare the means of the humus balance values determined by the two humus balance methods. Significance is defined as $p < 0.05$. A correlation analysis of the VDLUFA and STAND humus balance values and observed trends in SOC development was performed using a simple linear regression and the coefficient of determination, R^2. It is important to note that humus contents based on field observations are usually inferred from SOC measurements applying a constant conversion factor (Pribyl, 2010) because soil humus is not a single chemical compound or soil fraction that can be isolated. In theory, comparing changes in humus contents against SOC changes would therefore be a proper method for validation.

3 | RESULTS

3.1 | VDLUFA and STAND humus balance outputs

There were no significant differences in the humus balance values of crop rotations with organic and mixed fertilization that were determined by the two methods (Figure 1). This suggests that the VDLUFA and STAND humus balance models perform similarly for short-term observations. Differences in the distribution of the humus balance values among the five STAND site groups reflect the diversity among the agricultural practices at the long-term sites. When compared to calculations from the VDLUFA model, the humus balance values determined by STAND were slightly higher for site groups 2–4 and lower for site groups 5 and 6 (Figure 1). This indicates that the relationship between the humus balance values calculated by the models differ based on the farm's STAND site group.

The humus supply evaluations of the short-term observations were generally the same for both models (83.6% of crop rotations with mixed fertilization and 69.6% of crop rotations with organic fertilization were the same) (Figure 2). The instances in which the humus supply evaluations differed between the two models were depended on the site's STAND site group classification. For example, crop rotations at site groups 2–4 had higher humus supply levels when evaluated in STAND (Figure 2). As a result, crop rotations in site groups 2–4 were evaluated to have fewer interpretations of an undersupply of humus and more indications of an oversupply of humus by the STAND model. Conversely, crop

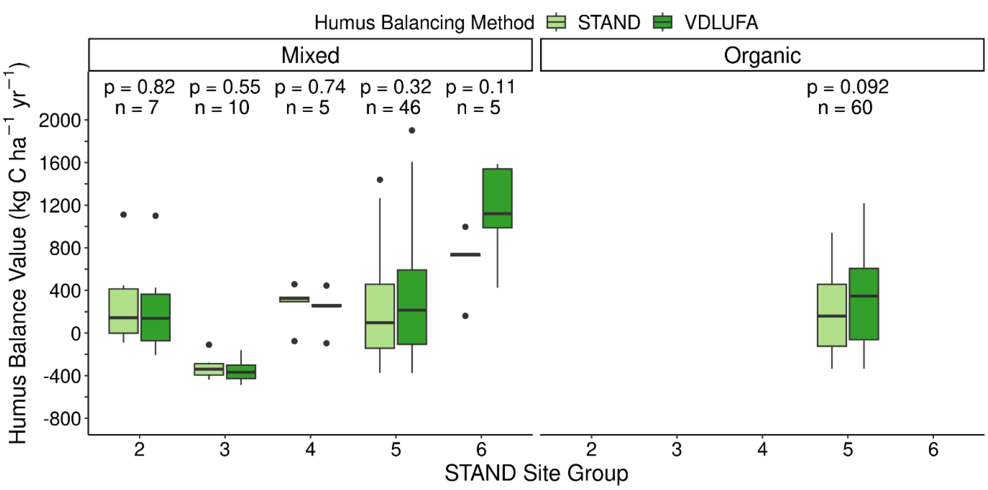

FIGURE 1 Box-plot analysis of humus balance values calculated with the STAND and VDLUFA methods (boxes indicate upper and lower quartiles and medians are shown by thick horizontal lines. Error bars represent minimum and maximum values, and outliers are indicated as dots). Results are separated for crop rotations with mixed and organic fertilization and for each STAND site group. Significance is defined as $p < 0.05$. n = number of crop rotations.

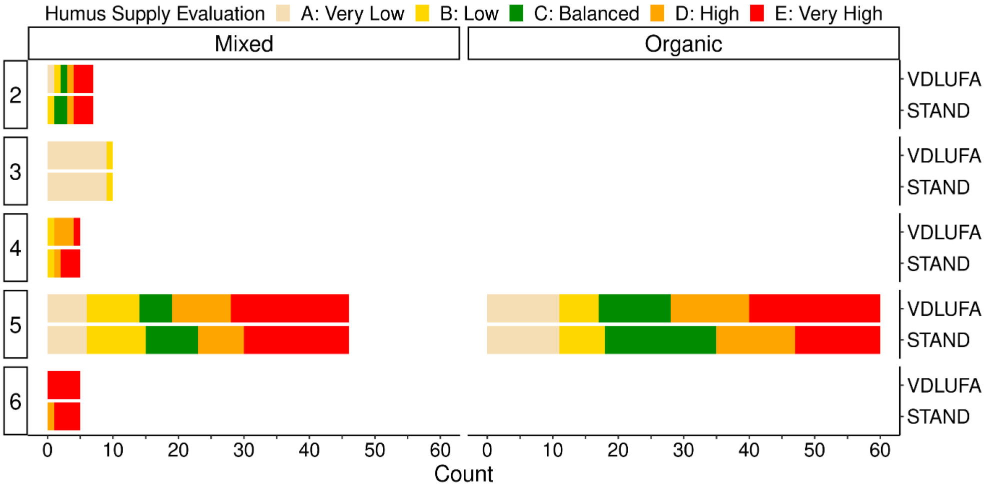

FIGURE 2 Humus supply evaluations of short-term observations with mixed and organic fertilization (count of crop rotation variants on x-axis) located in the five STAND site groups (y-axis), $n = 133$ crop rotation variants.

rotations at site groups 5 and 6 experienced the opposite trend. For these areas, evaluations by STAND resulted in fewer crop rotations with an oversupply of humus and more evaluations with a balanced or undersupply of humus when compared to the VDLUFA (Figure 2).

3.2 | Short-term vs. long-term crop rotations

Results of the comparison between change in SOC content and the VDLUFA and STAND humus balance values of short-term observations are similar, as the humus balance values derived by both methods showed no or poor correlation to observed SOC measurements in crop rotations with organic ($R^2 = 0.06$ for STAND and $R^2 = 0.05$ for the VDLUFA) and mixed ($R^2 < 0.01$ for both STAND and the VDLUFA models) fertilization (Figure 3). This is due to the fact that crop rotations with similar humus balances values experienced different directions of change in soil carbon. For example, there was considerable scatter in the observed change in SOC content among variants with similar humus balance values (Figure 3). Hence, there are many instances in which crop rotations evaluated to have the same humus supply group experienced different directions of change in SOC content. The mean standard error for the change in SOC content was 0.026% for the NABO sites, suggesting that SOC changes presented are significantly different from zero for most rotations. In case of the long-term experiments, the errors were larger (0.084% for p24A and 0.13% for DOK) and hence not all SOC changes differ significantly from zero. Nevertheless, the disagreement between humus supply groups and SOC changes remains. It is therefore unlikely that VDLUFA or the STAND humus balance methods can guarantee reliable inferences about SOC trends at time scales relevant to their application.

The correlation between the humus balance values and the observed change in SOC for long-term observations with mixed fertilization was still very poor for both humus balancing tools ($R^2 = 0.04$ for STAND and $R^2 = 0.06$ for the VDLUFA) (Figure 4, left column). The correlation of determination improved when the humus balance values of long-term observations with organic fertilization were compared with decadal soil carbon development ($R^2 = 0.68$ for STAND and $R^2 = 0.64$ for the VDLUFA) (Figure 4). Differences in the assessments of long-term observations with mixed and organic fertilization may reflect the greater diversity in the agricultural practices and local soil conditions among the crop rotations with mixed fertilization at the long-term sites (as only two sites, DOK and p24A, included plots that exclusively received organic fertilization, while all crop rotations at the NABO sites and some rotations at the DOK site received mixed fertilization).

While there is a stronger correlation between the change in SOC and the humus balance values for long-term observations with organic fertilization, the humus supply evaluations of each model do not logically match the SOC trends at a few sites. For example, there are a few instances in which the humus supply evaluations of crop rotations with organic fertilization experienced both a positive and a negative change in SOC content for the same humus supply group (e.g. for humus supply group D on the right column of Figure 4, there are points above and below x-axis). Crop rotations with organic fertilization that were evaluated to have balanced (supply group C), high (D) and, in one instance, a very high (E) humus supply by the VDLUFA humus balance model, experienced a negative change in SOC content (values below grey horizontal line in Figure 4). It is logical that crop rotations that were evaluated to have a balanced or excessive humus supply would have a non-changing or positive change in SOC content.

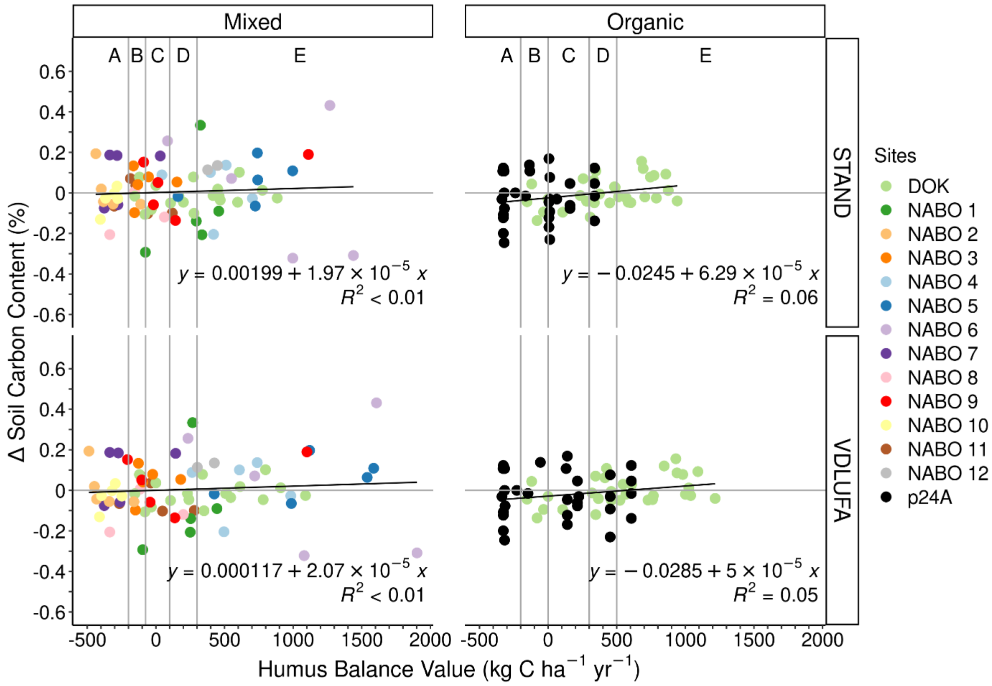

FIGURE 3 Correlation between humus balance value determined by the STAND (top) and VDLUFA (bottom) methods and observed change in soil carbon content of short-term observations with mixed (left) and organic (right) fertilization. The humus supply groups are labelled A–E at the top of each graph and represent the very low (A), low (B), balanced (C), high (D) and very high (E) humus supply evaluations. Standard errors for changes in soil carbon content for single crop rotations ranged from 0.023% to 0.22% for the DOK trial (mean 0.13%); 0.0084% to 0.063% for NABO sites (mean 0.026%) and 0.034% to 0.15% (mean 0.084%) for the p24A experiment. Because standard errors could not be calculated for every rotation (in some cases, only one composite sample was available), we do not show error bars.

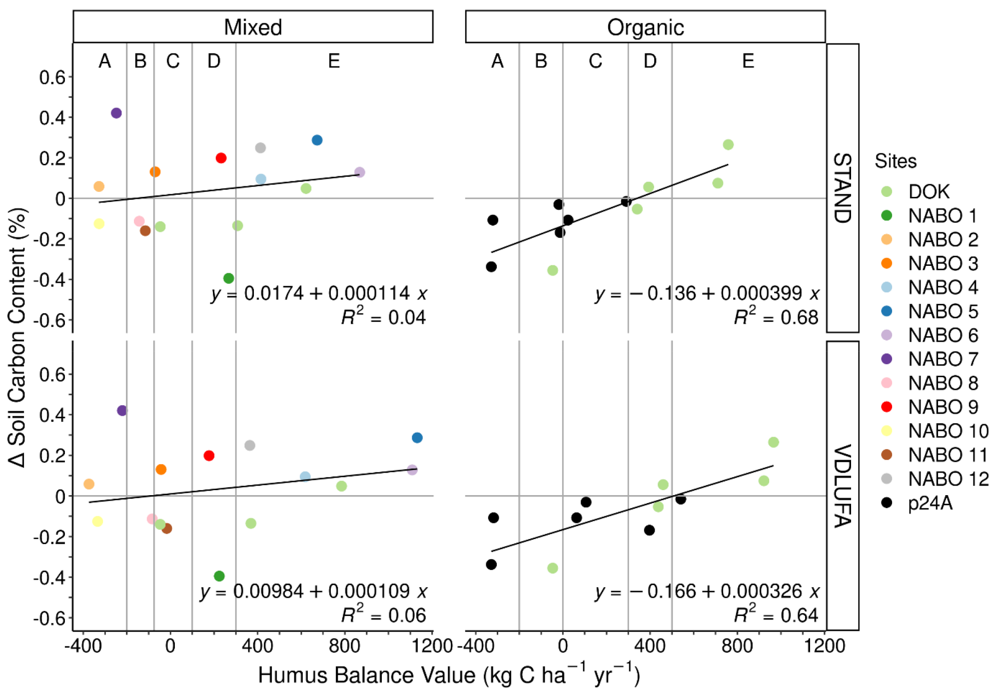

FIGURE 4 Relationship between humus balance values calculated with the STAND (top) and VDLUFA (bottom) methods and change in soil carbon content observed in long-term observations with mixed (left) and organic (right) fertilization. Humus supply groups A (very low), B (low), C (balanced), D (high) and E (very high) are labelled at the top of each graph.

3.3 | The impact of organic amendments

The discrepancy between the humus balance outputs and the observed SOC trends is further emphasized when the organic amendments supplied during the crop rotations were examined in more detail. Figure 5 shows the same comparison between the VDLUFA and STAND humus balance values and change in SOC content for short-term

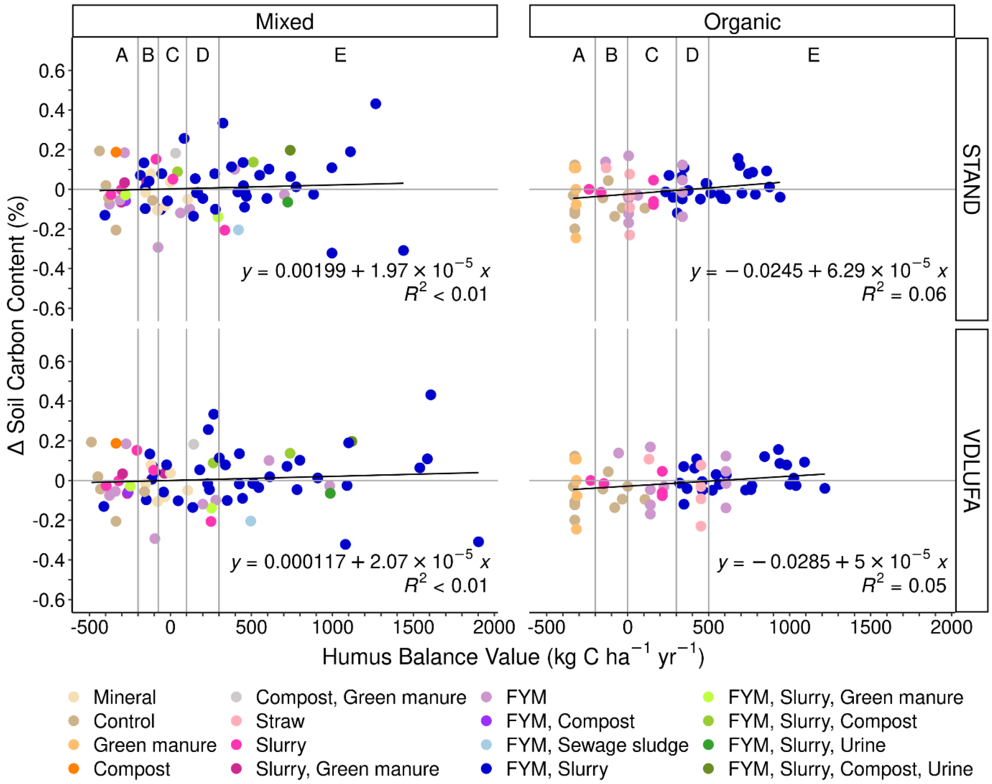

FIGURE 5 Comparison of the STAND (top) and VDLUFA (bottom) humus balance values and change in soil carbon content for short-term observations (i.e. single crop rotations of 5–6-year duration) at the 14 long-term sites. Crop rotations with mixed (left) and organic (right) fertilization are evaluated using the humus supply groups (A–E), which, respectively, represent very low, low, balanced, high and very high humus supply evaluations. Crop rotations are delineated by the type of applied organic material, wherein FYM stands for farmyard manure and crop rotations with mixed fertilization include treatments supplied with mineral fertilizer and treatments supplied with mineral fertilizer and the indicated organic material.

observations with an emphasis on the main fertilizer treatments. As was previously mentioned, crop rotations with mixed fertilization include mineral fertilizer treatments and those supplied with both mineral and organic fertilizer. On one hand, there were clear differences among the humus balance outputs of crop rotations supplied with different organic material. For example, the green manure treatments as well as the unfertilized control treatments had low humus balance values and very low (A) and low (B) humus supply evaluations, while most of the farmyard manure and slurry treatments had higher humus balance values and humus supply evaluations of high (D) and very high (E) (Figure 5). On the other hand, however, the ability of the calculators to distinguish between crop rotations supplied with different organic amendments was less clear for those provided with mixed fertilization. For both the VDLUFA and STAND models, there is a wide variation in the outputs of crop rotations supplied with mineral fertilizer and similar kinds of organic material. Namely, the humus supply level of the farmyard manure and slurry mixed fertilizer treatments spanned all five evaluation classes depending on the crop rotation (Figure 5). This indicates that although the calculators' ability to distinguish between the different organic amendments is marginally better for crop rotations with organic fertilization, neither the VDLUFA nor STAND are able to relate the differential impact of the mixed fertilizer treatments on humus development in short-term analyses. Similar results were observed for long-term evaluations (Figure S1).

The analysis with the best correlation is the comparison between the change in SOC content and the STAND humus balance values of long-term observations with organic fertilization (Figure 6). We found that plots treated with farmyard manure and slurry had higher humus balance values than the unfertilized control treatments or those treated with green manure and straw. The control treatments and those supplied with plant-derived organic amendments had humus supply evaluations of very low (A) and low (B) and experienced negative changes in SOC overtime (Figure 6). Conversely, treatments that were supplied with animal by-products such as the composted farmyard manure/slurry and rotted farmyard manure/slurry treatments had high (D) and very high (E) humus supply evaluations (Figure 6). However, there were multiple instances in which treatments that were

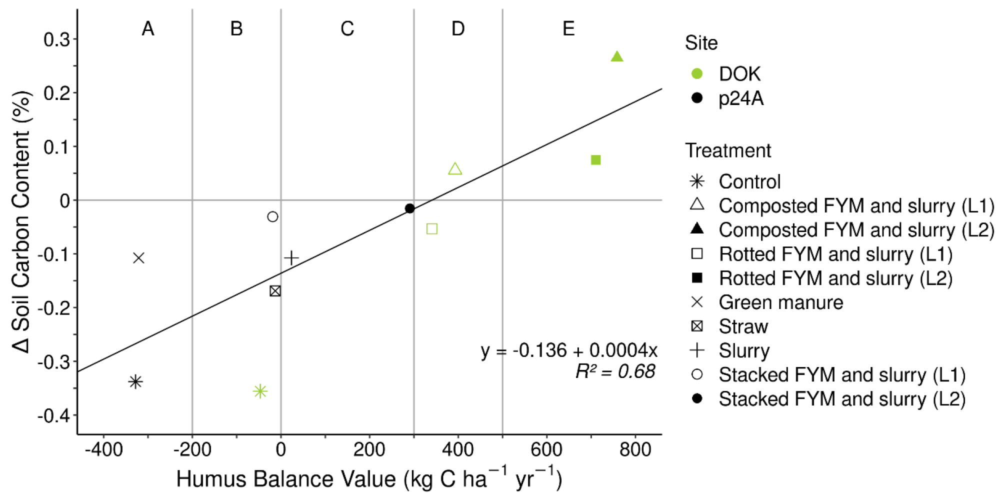

FIGURE 6 Comparison of the humus balance values determined with STAND and decadal change in soil carbon content of long-term observations with organic fertilization at the DOK (green) and p24A (black) experimental sites. The data are identical to Figure 4 (upper right panel), but here fertilizer treatments by different shapes (in which FYM means farmyard manure). Differentiation in the amount of organic fertilizer is indicated by levels 1 (L1) and 2 (L2), in which level 1 is exactly half of the applied amount of level 2. The labels A–E denote the evaluations of the humus supply groups (A (very low), B (low), C (balanced), D (high) and E (very high).

evaluated to have a balanced (C) or high (D) humus supply level experienced negative changes in SOC.

4 | DISCUSSION

4.1 | The function of the VDLUFA and STAND humus balance methods

The outputs of the VDLUFA and STAND humus balance calculators were not congruent with the observed changes in SOC for short-term observations. We found considerable scattering among the measured short-term changes in SOC content for crop rotations with similar humus balance values, which suggests that a definitive prognosis of the relationship between the output of humus balance calculators and the direction of measured change in SOC content cannot be reached. Although humus balance calculators are not designed to give quantitative outputs, they are meant to be used to make qualitative assessments. High/very high humus supply evaluations (humus supply groups D and E) are therefore expected to agree with positive SOC changes. The presented results show that not even this minimum requirement of the humus balance calculators is fulfilled. There are several possible sources of short-term variation in SOC at the farm scale, as results can be affected by differences in weather conditions prior to sampling, the strong positive or negative influence of a single crop in a given rotation, and farm management practices such as tillage (Bongiorno et al., 2019; Panagos et al., 2019). These potential sources of spatial and temporal variation are not captured by simple humus balance calculators. Additionally, in this study, the VDLUFA and STAND humus balance calculators were tasked to analyse short-term observations that span 5 or 6 years. Due to the large spatial and temporal variability in SOC, the duration of these short-term observations makes it challenging to capture minute changes in SOC. A careful sampling design was therefore applied (i.e. by using composite samples) and always sampling during the same time of the year (e.g. in spring in the case of NABO sites) to reduce SOC variability as good as possible. Still, the standard errors were rather large for the long-term trials p24A and DOK, but much lower for NABO sites (Figure 3). This was not surprising as the number of subsamples was a bit lower (10–20 vs. 25 per composite sample) in the two long-term experiments to keep the disturbance through coring as low as possible on these rather small plots.

While the correlation between the VDLUFA and STAND humus balance values and change in observed SOC slightly improved for long-term observations, discrepancies between these two variables may exist for similar reasons. For example, inferences about SOC trends may be difficult to determine because essential management and environmental parameters that influence SOC development are not included in simple tools like the VDLUFA and STAND. Even when the long-term sites are presumed to be at or near steady state, as they are at the NABO monitoring sites, in addition to primary drivers such as changes in agricultural management, SOC trends can be strongly influenced by site-specific soil parameters that are not included in the humus balance models such as the SOC/clay ratio (Gubler et al., 2019).

Furthermore, it is well established that long-term SOM development is influenced by numerous agricultural practices and pedoclimatic factors and processes (Kögel-Knabner & Amelung, 2021), which lead to considerable spatial variability in SOC (Mishra et al., 2010). Soil organic carbon accrual and depletion are also correlated with the type of plant inputs, which further contributes to spatial and temporal variability at the farm-scale (Usowicz & Lipiec, 2017). Spatial heterogeneity of carbon inputs and the random redistribution of organic matter through bioturbation can also contribute to spatial variability in SOC at the plot scale (Poeplau et al., 2022). Together, these effects present challenges for both direct on-site measurements and for the prediction of SOC change by soil models. As a result, a sufficient amount of soil samples is needed and/or detailed input data for modelling is required to obtain reliable predictions. Ideally, concurrent monitoring of soil is conducted over long time periods at the same sites with comparable methods and these assessments are accompanied by the collection of farm and soil management data.

4.2 | Differences from prior evaluation studies

Our findings and recommendations for use of the VDLUFA and STAND humus balance methods may differ from others because the association, or lack thereof, between observed SOC trends and the farm's humus supply evaluation is acknowledged. In both models, the crop rotation's humus balance value (the values shown, e.g. on the x-axis of Figures 3–6) is used to determine the humus supply group (A–E), from which the crop rotation's humus supply evaluation (very low-very high) is characterized (Kolbe, 2010; Körschens et al., 2004). Within the VDLUFA and STAND humus balance models, humus supply is evaluated based on the risk of either negative impacts on yield security or an increase in the soil's N mineralization potential (Körschens et al., 2004). When drawing a link between the humus supply evaluation and change in SOC for a particular crop rotation, a logical connection must be established. For example, a very low or low humus supply evaluation relates to a negative change in SOC and decreased crop yield because an inadequate supply of humus during the crop rotation directly influences the soil's nutrient supply and indirectly impacts soil physical, chemical and biological properties that stimulate root growth and thus biomass production (Lal, 2020). Conversely, a balanced humus supply evaluation is indicative of the conservation or increase in SOC as an adequate humus supply promotes yield security and optimal soil function (Oldfield et al., 2019). Humus supply evaluations of high or very high do not relate to SOC development but are rather assessments of the risk an agricultural practice poses to environmental harm (Körschens et al., 2004). Although an increased supply of humus can promote SOC sequestration through chemical and physical mechanisms such as the formation of organo-mineral associations and the stabilization via aggregation (Baldock & Skjemstad, 2000; Six et al., 2002; Sollins et al., 1996), the high and very high VDLUFA and STAND humus supply evaluations simply characterize the risk the farm poses to nutrient leaching, not the amount of humus that remains in the soil. The tools should therefore not be used to infer changes in SOC, as they were not designed for this purpose. Furthermore, focus on the correlation between the models' humus balance value and the observed change in SOC may also lead to incorrect interpretations of the capability of these simple tools. In contrast to the present study, prior investigations of the VDLUFA and STAND humus balance methods have generally found strong, positive correlations between the humus balance values of short-term observations and the observed change in SOC content (Beuke, 2006; Brock et al., 2016; Kolbe, 2012, 2015). Based on the strength of these correlations, these simple humus balance models were recommended for use in assessments that examine the impact of agricultural practices on a farm's humus supply. However, it is important to note that the R^2 value is an evaluation of the performance of the linear regression and not a measure of the models' performance as it is interpreted in some validation studies (Garsia et al., 2023). For example, even when a strong, positive correlation between the models' humus balance value and the measured change in SOC is observed, assessments of individual crop rotations can be incorrect. This is illustrated in our assessment of long-term observations with organic fertilization (Figure 6), in which there were two observations that had balanced humus supply evaluations (humus supply group C) and negative changes in SOC content, despite the rather strong correlation between the two variables ($R^2 = 0.68$). Therefore, conclusions about the applicability of the models that have been inferred based on the correlation between the humus balance value and measured change in SOC content are flawed because they fail to consider of the relationship between the humus supply evaluation, which may not align with the observed SOC trend.

4.3 | Practical application of the VDLUFA and STAND humus balance methods

This study focuses on the effect of different types and amounts of organic fertilizer on humus balance evaluations. This distinction is important to highlight because it is one of the key differences between the VDLUFA and STAND humus balance methods (Brock et al., 2013). In addition to regulating the humus coefficients of crops based on the different site locations, STAND was developed to mitigate overestimation of the humus contribution from organic amendments by adjusting the humus coefficient based on the fertilization amount of the organic material (Kolbe, 2010, 2012). Similar findings of location-dependent differences in the humus balance outputs of a few crop rotations have been reported by Kolbe (2012). Overall, however, there were no significant differences in the STAND and the VDLUFA humus supply evaluations for the majority of the crop rotations examined in this study. This means that while the VDLUFA and STAND differ with regard to the humus coefficients for crops and organic materials, the results of these models are not significantly different and STAND does not outperform the VLDUFA humus balance model.

The VDLUFA and STAND humus balance methods were able to assess the relative impact of different fertilizer treatments, but only under certain circumstances. Our findings agree with those of Brock et al. (2016), who found that the VDLUFA humus balance method is sensitive to differences in agricultural practices that are related to organic matter additions. In our study, these results were more evident for crop rotations with organic fertilization due to the design of the DOK and p24A experiments which allowed for direct comparisons of the effect of the fertilizer treatments. At the two long-term experimental sites, the crop selection for a given crop rotation was the same for all treatments, and the fertilization intensity of some treatments changed only slightly over time (Krause et al., 2022; Maltas et al., 2018). Conversely, the agricultural practices among the crop rotations with mixed fertilization were more varied, both in terms of the crop selection and fertilization management over time.

The effect of different crop rotations on determinations of the farm's humus supply is not examined in this present study. However, a few studies have indicated a need for adjustments to the humus coefficients for crops in simple humus balance methods (Erhart et al., 2021; Götze et al., 2016). For example, Götze et al. (2016) examined the effect of crop rotation on SOM development by comparing the humus balance values determined by the Dynamic Humus Unit Method to the total organic carbon (TOC) content of soils with crop rotations that had increasing proportions of the humus demanding sugar beet crop. This analysis of soil development over 41 years found that although the humus balance values were positively and significantly correlated with TOC, the humus balance values overestimated the actual organic matter demand of the specific crop rotations (Götze et al., 2016).

Long-term SOC trends at DOK exemplifies the capabilities and limitations of the VDLUFA and STAND evaluation criteria. In an analysis of SOC trends over 42 years, Krause et al. (2022) found that SOC content increased in the composted farmyard manure/slurry treatment as well as in the rotted farmyard manure/slurry treatment, remained constant in the stacked farmyard manure/slurry treatment and decreased in all of the other treatments over time. In the present study, long-term observations with unfertilized treatments at the DOK site had a low humus supply evaluation and therefore are in logical alignment with the long-term trend of SOC loss (Figure 6). By contrast, we found that crop rotations supplied with composted farmyard manure/slurry as well as those supplied with rotted farmyard manure and slurry had high and very high humus supply evaluations (Figure 6) and suggest an increased risk for N leaching. However, at the DOK site, nitrogen (N) leaching was found to be higher, but not significantly different in the composted farmyard manure/slurry and rotted farmyard manure and slurry treatments than in the mineral and unfertilized treatments (Autret et al., 2020). Although there was a positive long-term change in SOC for these particular treatments, this is not indicative of N leaching, and the humus evaluation criteria may only serve as a rough indicator of the impacts of agricultural practices on the farm's humus supply.

4.4 | Recommendations for future decision-support tools

The inability of the VDLUFA and STAND humus supply evaluations to reflect directions of change in SOC suggests that these humus balance models are not effective predictors of observed SOC trends. Mechanistic models such as RothC may be better equipped for this purpose because they incorporate parameters such as the varying quality of SOC inputs, initial SOC content, the continuous breakdown of formed organic matter, monthly temperature and precipitation, and use of cover crops in their estimations of carbon flux between different SOC pools (Dechow et al., 2019; Leifeld et al., 2009). However, there are some complications with the use of more complex models for assessments of agricultural practices at the farm-scale. For example, the ability of these tools to predict SOC dynamics is subjected to the model's default parameter values and the allometric functions used to quantify changes in SOC over time (Dechow et al., 2019). The selection of such parameters is difficult at the farm-scale due to the variability among sites. Also, the inclusion of such detailed soil, climate and management data renders mechanistic models nonviable as tools for farmers. For instance, site-specific input data such as initial SOC stock and measured clay content, detailed information on historic and current agricultural management (crop types, annual information on yields, amounts and type of organic matter addition), and meteorological information with a daily/monthly resolution are all required to account for potential changes in humus balances associated with these factors. Therefore, mechanistic models are not a panacea for assessments of agricultural practices for farmers assuming they have to gather these data themselves, but rather for experts and only under the condition that sufficient measured data are available.

Future decision-support tools may include humus balancing calculators that have undergone further refinement for use at the local level or simplified versions of the more complex carbon models. Possible improvements to simple humus balancing tools may involve the inclusion of more management and site-specific parameters that influence the underlying mechanisms of SOC change such as prior land use history, initial SOC content and SOC decay dynamics. Such methods are currently being developed and will serve as useful tools that contribute to climate mitigation efforts by maintaining and improving humus content in arable environments. For example, as part of the CarboCheck humus management tool, the CPix application allows users to determine initial soil humus content with a smartphone (Carbocheck – Humuswirtschaft Digital, n.d.). This application uses the geolocation data imbedded in an image of the topsoil to obtain local soil and climate parameters from a database of long-term sites. The geodata is then combined with the image's spectral colour data in an algorithm to estimate initial soil humus content (Fischer, 2020). Alternatively, mechanistic models can be simplified to reflect the format of simple humus balance models for more applicable use at the farm-scale. For instance, Dechow et al. (2019) applied two separate calibration procedures on data gathered from 36 long-term experimental sites located in Central and Northern Europe to modify model parameters in RothC that represent the quality of carbon inputs from crop residues and the humification coefficients for different organic amendments. These parameters were then used to develop a simplified model structure that incorporates the effects of carbon input and decomposition by roots and stubbles, initial SOC at steady state and the effect of organic amendments on SOC content (Dechow et al., 2019). Lastly, geospatial data platforms such as FarmMaps and the Flanders Research Institute for Agriculture, Fishers and Food's Bodempaspoort ('Soil Passport') have employed a combination of these approaches. These platforms allow farmers to simulate temporal changes in SOC stock with RothC using user provided current/alternate farm management data and site-specific soil data that are gathered from public/private databases (Annys et al., 2022; Lesschen et al., 2020).

5 | CONCLUSION

To support effective decision making at the farm-scale humus balancing tools must be accurate, have the capabilities to assess a range of agricultural practices and require input data that are easily accessible to farmers. By comparing the VDLUFA and STAND humus balance outputs to SOC measurements, we observed that the two methods performed similarly and STAND did not outperform the VDLUFA at long-term sites in Switzerland. Additionally, we showed that these particular humus balancing methods should not be used to draw inferences about SOC dynamics, especially of individual short-term observations, due to the inaccuracy of the calculators. While VDLUFA and STAND humus balancing calculators are capable of differentiating among long-term crop rotations with different organic fertilizer treatments, caution should be used when making inferences about the impact of management practice on the site's soil sequestration capacity and nitrogen use efficiency. Future research on this topic may consider the continued validation of both mechanistic soil carbon models and simple humus balance methods, particularly using data gathered from different soil types that have experienced complex agricultural practices overtime. Furthermore, it is necessary to implement critical information and calculation routines for humus balance predictions that are currently lacking in simple tools like the VDLUFA and STAND humus balance calculators. Alternatively, efforts could focus on reducing information required for the application of tools that demand more input data and make them user friendly for farmers. Ultimately, both approaches rely on the collection of SOC measurements as information on the initial SOC condition is very critical for any type of prediction.

AUTHOR CONTRIBUTIONS

Shauna-kay Rainford: Writing – review and editing; writing – original draft; formal analysis; methodology; visualization; investigation. **Jens Leifeld:** Conceptualization; writing – review and editing; project administration; supervision; funding acquisition. **Sonja Siegl:** Conceptualization; methodology; writing – review and editing; funding acquisition. **Steffen Hagenbucher:** Conceptualization; writing – review and editing; funding acquisition. **Judith Riedel:** Writing – review and editing; funding acquisition.

Thomas Gross: Data curation; writing – review and editing. **Urs Niggli:** Writing – review and editing. **Sonja G. Keel:** Investigation; conceptualization; methodology; writing – review and editing; project administration; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data from the long-term experimental sites are available upon request from the respective Project Leaders of DOK and p24A experiments, Jochen Mayer and Luca Bragazza. Data regarding the agricultural practices and soil organic carbon content at the NABO sites are not publicly available to protect the privacy and anonymity of the farmers who participate in the long-term monitoring program.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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