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An Approach for Describing the Effects of Grazing on Soil Quality in Life-Cycle Assessment

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Abstract: Describing the impact of farming on soil quality is challenging, because the model should consider changes in the physical, chemical, and biological status of soils. Physical damage to soils through heavy traffic was already analyzed in several life-cycle assessment studies. However, impacts on soil structure from grazing animals were largely ignored, and physically based model approaches to describe these impacts are very rare. In this study, we developed a new modeling approach that is closely related to the stress propagation method generally applied for analyzing compaction caused by off-road vehicles. We tested our new approach for plausibility using a comprehensive multi-year dataset containing detailed information on pasture management of several hundred Swiss dairy farms. Preliminary results showed that the new approach provides plausible outcomes for the two physical soil indicators “macropore volume” and “aggregate stability”.

Keywords: soil structure; macropore volume; aggregate stability; compaction; modeling; grazing animal; trampling

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1. Introduction

Soils are a key component of terrestrial ecosystems and provide multiple ecosystem services to humans, such as provisioning of food, timber, and freshwater. Soil is a natural resource and the basis for agriculture and agricultural food production. Thus, quantitative and qualitative protection of soils is essential not only for food security, but also for other soil functions such as supporting biodiversity, storing and filtering water, and sequestering carbon. Protection of soils can be achieved by sustainable agricultural land management, which prevents degradation of soils, safeguards food production, and preserves soil functions. Soil degradation, particularly linked to land use and land-use change due to agricultural practices, is a serious problem worldwide [1–3]. To maintain a multifunctional productive soil, it is, therefore, essential to reduce negative impacts on soil quality.

Soil degradation of grassland by grazing livestock, through defoliation, trampling, and excretion, is a crucial problem in many countries. The negative impact of trampling on soil physical properties is of special interest, as intensive livestock farming systems continue to increase worldwide. Ignoring soil degradation caused by grazing cattle may be a critical oversight, because permanent grassland comprises, e.g., 40% of agricultural area in Western Europe and 70% in Switzerland. This grassland is often used as pasture for grazing animals. About 20% of the world’s pasture areas are considered to be degraded as a consequence of overgrazing and associated erosion and compaction [4]. However, most of these degraded pastures are located in dry areas; thus, their degradation is mainly related to wind and water erosion, and not to structural damage. Nevertheless, Reference [5] estimated that 0.83 million km^2 of pastureland worldwide is physically degraded due to overgrazing.

Life-cycle assessment (LCA) can help to identify and understand the environmental impacts induced by human activities such as agricultural production [6–8]. LCA studies consider the use of natural resources (e.g., energy, freshwater, land, phosphorus, and potassium) and environmental impacts such as global warming, ozone depletion, deforestation, land competition, acidification, eutrophication, and ecotoxicity.

However, detailed assessment of the impact of farming activities on soil quality is often overlooked. Although a substantial number of soil quality models were developed [9], only a few fulfil one of the major requirements in LCA designed for agricultural systems, i.e., that the impacts of different agricultural management options should be visible in soil quality assessment. To fill this research gap, the Swiss Agricultural Life-Cycle Assessment for Soil Quality (SALCA-SQ) approach for assessing the effects of agricultural management practices on soil quality in LCA was developed [10]. The SALCA-SQ method characterizes the impacts of soil management practices on the holistic quality of soils using nine indicators, covering physical, chemical, and biological aspects of soil quality. The physical state of a soil is usually assessed by soil properties such as bulk density, total porosity, macroporosity, water infiltration rate, penetration resistance, and aggregate stability. The last two parameters are linked to soil strength, i.e., the capacity of a soil to resist an applied stress without experiencing physical deformation.

Soil compaction due to wheeling by vehicles and due to trampling by grazing animals is a physical impact resulting in direct negative effects on most physical soil properties, causing soil degradation [11]. According to Reference [12], cows can exert static stresses on the soil surface of up to 200 kPa, because their weight is transferred to the surface only in the rather small claw contact areas. These dynamic stresses can be significantly enhanced during movement of the cow (when not all claws are in contact with the soil surface) or on uneven soil surfaces. References [13,14] concluded that the dynamic stress caused by a moving cow is approximately twice that caused by an equivalent stationary cow. The stresses caused by animals' claws or hooves may easily exceed those caused by wheeled agricultural vehicles, and they are likely to be more widely spread over the field surface than wheel tracks of one specific mechanized field operation [15]. However, the soil contact area of a single vehicle wheel is much larger than that of a single hoof.

Experiments showed that compaction effects caused by animal trampling are confined to the topsoil layer of approximately 20 cm depth [16]. Some studies found that the highest impact on soil structure caused by grazing animals takes place in the top 5-cm soil layer [17,18] and is generally due to soil poaching under very wet soil conditions. Reference [19] found that compaction by horses is more serious than compaction by cattle, because horses' hooves have a smaller soil contact area than the claws of cattle. They also found that sheep have a much lower individual impact on soil compaction because of their low ratio of body weight to soil contact area, resulting in lower stresses in the soil contact area [19].

Compaction tends to decrease the volume and continuity of large pores (macropores, with diameter >30 µm), thereby limiting water and air infiltration into soil and transport within soil. As a consequence, surface runoff of water increases [20] and, with it, the risk of erosion. Macropores are less stable due to their greater size and, therefore, more susceptible to deterioration by mechanical impacts than smaller pores [18,21]. Crushed macropores are the result of a permanent plastic deformation of soil structure, which persists after the stress is removed. References [21,22] found that, because macropore volume is very sensitive to mechanical impacts, it is well suited for characterizing the impact of soil structural quality in general and of soil compaction in particular. Reducing the number and volume of macropores leads to increased bulk density, which in turn leads to increased penetration resistance, thereby reducing root penetration in the soil and plant growth below and above the soil surface.

Grazing animals may also disrupt soil aggregates, resulting in reduced aggregate stability [16,23]. This increases the risk of sealing of the soil surface and, therefore, the risk of water runoff and water erosion. Reference [19] found a distinct negative correlation between aggregate stability and soil bulk density (induced by compaction due to trampling cattle). Reference [24] concluded that, during the destruction of aggregates, water is squeezed out of the aggregates due to the loss of pore space.

Soil moisture content strongly affects a soil's vulnerability to compaction. As a soil becomes drier, its strength increases and, therefore, stress transfer into deep subsoil layers is reduced, increasing the negative impacts on upper subsoil structure [20,25]. However, as pointed out by Reference [23], aggregate stability tends to decrease with increasing soil moisture content. It is well known from the literature that animal trampling can lead not only to soil compaction, but also to structural damage, resulting in surface sealing [14]. Another consequence of animal trampling under (very) wet conditions may be deep hoof imprints with kneading of soil structure, as well as serious damage to plant cover [18].

Based on these findings, it is clear that the impact of soil compaction by trampling animals on soil structure is controlled by (1) soil properties and conditions such as texture, structure, type, and moisture; (2) grazing characteristics and pasture management such as stocking density, grazing duration, animal weight, and stocking management; and (3) sward composition. Thus, a generally applicable (process-oriented) model should consider these variables as input parameters in an appropriate way.

Compaction of soils due to heavy machinery is considered in a number of soil quality models [9,26], but the physical impacts on soils caused by grazing animals are yet to be incorporated into soil quality models in a satisfactory way. It is, thus, of the utmost importance to assess possible trampling effects of grazing animals on the structure of grassland soils in soil quality models such as SALCA-SQ. Although the effect of grazing animals on soil physical properties was investigated for many different soils and animal species in a number of previous studies, surprisingly little was done to produce a generalized description of all processes involved [21]. In particular, attempts to model compaction effects of trampling animals in a process-oriented quantitative physical framework are rarely described in the literature.

This paper describes a novel modeling approach to estimate the compaction effect of grazing animals due to trampling, using a quantitative soil mechanical model. The approach can be used in a decision support tool that helps farmers assess potential soil compaction due to grazing and to adopt sustainable grazing management. The effects of animal trampling on pasture productivity or on erosion risk are not considered in the current model. Other factors excluded from the model are animal-induced changes to the nitrogen (N) cycle, which are handled in other SALCA modules [27,28], and the impact of grazing animals on chemical and biological soil properties [10].

This remainder of this paper is structured as follows: we start with a short description of the SALCA-SQ approach, in order to explain the functioning of the SALCA-SQ model. The next section describes our new approach for estimating the soil compacting effect of grazing animals in detail, followed by a plausibility check based on data from several hundred Swiss dairy farms in the period 2011–2014. We then discuss the findings and finally present some conclusions, focusing on issues to be included in future refinements of the approach.

SALCA-SQ

The SALCA-SQ method assesses the impact of agricultural soil use and management on soil quality by selecting nine pivotal soil properties (or "soil quality indicators") [10]. These are separated into physical (rooting depth, macropore volume, and aggregate stability), chemical (organic carbon, heavy metals, and organic pollutants), and biological (earthworm biomass, microbial biomass, and microbial activity) properties. Use of the combined set allows for holistic assessment of soil quality by considering irreversible impacts on soil structure caused by agricultural management practices within a typical crop rotation period of 6–8 years. The selection criteria for this set of indicators comply with standard 14044 of the International Organization for Standardization [29], which states in particular that (1) the scientific and technical validity of the characterization model for each indicator must be guaranteed, and (2) the indicators must have a direct impact on soil functions. In SALCA-SQ, these indicators are estimated by modeling the impact pathway from inventory data (management practices and site properties represented by soil and climate properties) for each of the nine soil quality indicators. In detail, the modeling flow of SALCA-SQ comprises the following five steps:

1. Assign the various management practices (e.g., soil tillage, fertilizing, harvesting) to impact classes (e.g., soil erosion, soil compaction by wheeling). Impact classes are generally influenced by more than one management practice. This procedure is called "classification" in LCA according to ISO 14040.
2. Quantify the effects of each management practice on the impact category (by categorization or by using threshold values based on expert judgement). This is called "characterization" in LCA according to ISO 14040.
3. Group environmental processes to one or more soil quality indicators (first-level environmental category indicator, "first-level" midpoint).
4. For every soil quality indicator, weigh the effects of each single environmental process according to its relevance and add up the weighed effects.
5. Aggregate the effects on all nine soil quality indicators to a final single score indicator for soil quality ("second-level" midpoint), using a highly non-linear aggregation scheme. This aggregation step requires sophisticated calculations because overall soil quality cannot be represented by a simple arithmetic mean of all indicators and because soil functions may be limited by a single indicator, e.g., more active soil microorganisms cannot compensate for reduced rooting depth [10].

Each of the nine soil quality indicators is formed by the combined effects of management practices that (1) increase soil quality and (2) decrease soil quality. Figure 1 illustrates this procedure for the effects of the two management practices "slurry application" and "grazing" on the soil quality indicator "aggregate stability". From the diagram, it is evident that the farmer can positively influence the soil quality indicator by avoiding unfavorable management practices and by using good management practices instead.

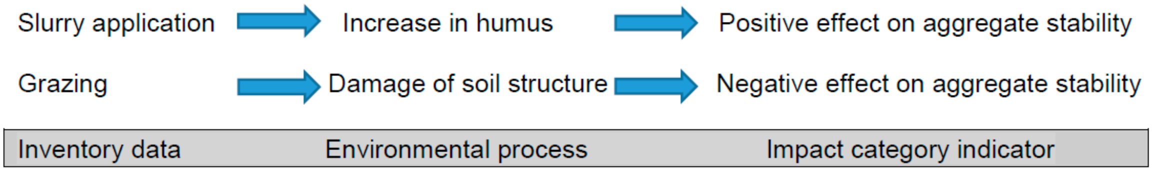

Figure 1. Illustration of the procedure to assess the effects of the two agricultural management practices "slurry application" and "grazing" on soil aggregate stability.

This procedure does not aim at providing absolute values for the soil quality indicators, but rather assesses changes in indicator values due to different agricultural management practices, thus allowing comparisons. The impact on biodiversity is not part of the SALCA-SQ model, because this topic is covered by SALCA-Biodiversity [30].

2. Materials and Methods

The proposed new approach is based on the same soil mechanical principles as applied in SALCA-SQ for estimating the extent of soil compaction caused by field traffic by vehicles. It is a semi-quantitative approach that estimates the compaction impact on the two physical soil quality indicators "macropore volume" and "aggregate stability", which are generally used for describing structural effects of soil compaction. Possible negative impacts I_{pk} for grazing event k on pasture p on macropore volume and aggregate stability were estimated and entered in a look-up table (Table 1) based on (1) the percentage of trampled area, PtA, in the pasture during a grazing period, and (2) the vertical soil stress at 10 cm soil depth (σ_z = 0.1 m) under the hooves or claws of a grazing animal. Below, we provide a detailed description of how to compute the two quantities PtA and σ_z = 0.1 m.

Movement of animals is assumed to be randomly distributed in the pasture area, i.e., a given pasture area can be trampled more than once during a grazing period. The variable PtA can be estimated by typical (measurable) animal characteristics such as the hoof or claw area and the mean daily walking distance.

$$PtA = n_{anim} \times \frac{2 \times \frac{DWD}{SL} \times a_{claw}}{a_{past}} \times GrPe \times \frac{DGH}{24} \times 100, \tag{1}$$

where n_{anim} = number of animals, DGH = daily grazing hours (hours), DWD = mean daily walking distance (m), SL = mean stride length (m), $GrPe$ = grazing period (days), a_{claw} = average hoof or claw contact area (m^2), and a_{past} = pasture area (m^2).

The percentage of trampled area (PtA) accounts for the fact that walking cattle are characterized by two claws being simultaneously on the ground. For the calculations performed in this study, an average hoof or claw contact area of 90 cm^2 [13], a mean stride length of 81 cm [31], and a mean daily walking distance of 8 km [32] are assumed.

Stress propagation into the soil is described by the concentration factor ν [33,34]. Typical values for ν in the target soil depth of z = 0.1 m are provided in a look-up table for different soil conditions (soil moisture and soil strength) (Table 2). Pastures are always characterized by firm soil, and the soil moisture is derived in a very simplified manner from look-up tables using three variables: month of the year, soil texture class (sandy soil, silty soil, loamy soil, clayey soil), and climate suitability for agricultural use (considering air temperature, sum of precipitation, and duration of vegetation period). Table 3 provides an overview of the used soil parameters along with their ranges of possible values. Higher ν values are associated with lower values of soil strength, resulting in downward stress propagation and therefore compaction in deeper soil layers. The concentration factor ν allows for computation of soil stress at 10 cm soil depth, σ_z = 0.1 m, for a given stress σ_{surf} in the contact area of the animals' hooves or claws according to Equation (2).

$$\sigma_z = \sigma_{surf}\left[1 - \cos(\alpha)^{\nu}\right], \tag{2}$$

where z = soil depth (m), σ_z = stress at soil depth z (Pa = N·m^{-2}), σ_{surf} = surface stress (Pa; see Equation (3)), ν = concentration factor, and $\alpha = arctan(r/z)$, with r = half width of hoof or claw (m).

Surface stress, σ_{surf}, under a single claw is derived from the claw contact area and the animal weight.

$$\sigma_{surf} = \frac{m_{animal} \times g}{2 \times a_{claw}}, \tag{3}$$

where m_{animal} = mass of animal (kg), a_{claw} = claw (or hoof) area (m^2), and g = gravitational constant (9.81 m·s^{-2}).

The surface stress σ_{surf} in Equation (3) accounts for the fact that walking cattle are characterized by having two claws simultaneously on the ground. For the calculations performed in this study, the mean weight of a cow is set to 700 kg. However, the model can easily be applied to other types of livestock, such as horses, fattening bulls, or breeding cattle.

For the physical soil quality indicators "macropore volume" and "aggregate stability", the compaction effect I_{pk} is categorized into three classes: 0 = no effect, −1 = unfavorable, and −2 = very unfavorable, according to Table 1. This classification of I_{pk} values is based on expert judgement and follows the procedure for assessing the compaction effect caused by wheeling according to Reference [10].

The total impact I_{farm} of all individual compaction impacts on a single farm (for a period of one year) is then computed by adding together the area-weighted values of I_{pk} for all pastures p and all grazing periods k on a specific farm.

$$I_{farm} = c_{calib} \times \sum_{p=1}^{n_k} a_p \sum_{k=1}^{n_p} I_{pk} = c_{calib} \times \sum_{p=1}^{n_k} I_p, \tag{4}$$

where c_{calib} = calibration constant, a_p = fraction area of pasture p of the total farm's grassland area, n_k = number of grazed pastures on the farm, n_p = number of grazing events on pasture p, I_{pk} = (scaled) impact on soil compaction for grazing event k on pasture p, and I_p = impact on soil compaction for all grazing events k on pasture p.

A stronger negative value of I_{farm} denotes a higher expected compaction impact. Based on Equation (4), in a concrete computation of I_{farm}, the impacts of the n_p grazing events of pasture p are firstly computed, combined, and weighted with the fraction area a_p of pasture p, resulting in I_p. The values of I_p for all n_k pastures are then computed and added together. The calibration constant c_{calib} is necessary to numerically adjust the value for I_{farm} to the factor effect calculations in SALCA-SQ, which consider both negative and positive effects of management impacts on the physical soil quality indicators "macropore volume" and "aggregate stability" (see above description of the SALCA-SQ model). In the present case, c_{calib} is set to 0.01, ensuring that typical maximal negative effects of grazing in the topsoil are of the same order of magnitude as typical negative effects caused by heavy machinery.

Table 1. Look-up table based on expert judgement for classification of the compaction impact I of grazing cows: 0 = no effect; −1 = unfavorable; −2 = very unfavorable.

Percentage of Trampled Area (*PtA*) (%)	Vertical Soil Stress (under the Claws) at 10 cm Soil Depth, σ_z (kPa)					
	<30	30–59	60–89	90–119	120–149	≥150
>50	0	−1	−1	−2	−2	−2
26–50	0	0	−1	−1	−2	−2
10–25	0	0	0	−1	−1	−2
<10	0	0	0	0	−1	−1

Table 2. Look-up table for concentration factor ν as a function of soil moisture and soil firmness.

Soil Moisture	Soil Firmness		
	Loose	Semi-Firm	Firm
Dry	4	2	2
Moist	5	3	2
Wet	6	4	3

Table 3. Soil parameters, their definition, and ranges of possible values. Soil moisture is defined using the matric potential. Soil firmness is characterized by the soil's precompression stress. Soil texture class is defined by the soil texture triangle. SMA = soil matric potential; PS = precompression stress; CL = clay; SI = silt. [1] Example: ploughed soils. [2] Example: arable crops before harvest. [3] Example: Swiss soil texture triangle [35].

	Possible Values	Definition	Function of
Soil moisture	Dry Moist Wet	SMA < −300 hPa −300 hPa < SMA < −60 hPa SMA > −60 hPa	• Soil texture, soil organic matter, soil type • Climate • Soil cover and management
Soil texture class [3]	Loamy Clayey Silty Sandy	CL 15–40%, SI < 50% CL > 40%, SI < 50% SI > 50% CL < 15%, SI < 50%	• Parent material • Soil genesis
Soil firmness	Loose [1] Semi-firm [2] Firm	PS < 50 kPa 50 kPa < PS < 150 kPa PS > 150 kPa	• Soil texture, soil organic matter, soil structure • Soil cover and management

The final methodological step involves categorization of the I_{farm} values into the three categories "no effect", "unfavorable", and "very unfavorable" for the two physical indicators "aggregate stability" and "macropore volume". I_{farm} values between −1.0 and 0.0 are placed in the category "no effect" for aggregate stability (the corresponding range for the macropore volume is [−1.5, 0.0]), while I_{farm} values below −3.0 for aggregate stability and below −5.0 for macropore volume are categorized as "very unfavorable". The determination of those threshold values follows the same logic as presented in Reference [10] for classifying the impact of heavy machinery on aggregate stability and macropore volume.

Data Used for Plausibility Tests

The plausibility of the new approach for assessing the compaction effects of grazing animals was tested using an extensive dataset on several hundred Swiss farms obtained from the Swiss Agri-Environmental Data Network (SAEDN). This dataset contains detailed information on stocking rates and grazing periods on Swiss farms. The plausibility testing was based on data collected between 2011 and 2014, with annual samples of between 254 farms (in 2014) and 297 farms (in 2011), resulting in 1095 data samples at the farm and year level (multiple counting of farms providing data for more than one year during the period 2011–2014). We excluded 126 farms due to missing data or because the farm did not graze cattle, yielding 969 data samples at the level of farm and year. Of these data samples, 19%, 34%, and 47% were located in valley, hilly, and mountain regions, respectively.

The dataset contained the stocking densities and grazing periods for approximately 24,450 single grazing events, i.e., periods of consecutive days with grazing, adding up to almost 690,000 grazing days or 1900 grazing years. Table 3 summarizes some descriptive statistics on the SAEDN dataset (only farms with complete datasets).

Figure 2 displays the probability density function for the same three variables as presented in Table 4. The descriptive statistics clearly show that the SAEDN dataset covered a wide range of grazing management options. The stocking density for the full sample was on average 11.1 livestock units per hectare (LU/ha), with a standard deviation of 15.4 LU/ha (Figure 2a). The positive skewness of the stocking density data indicates that most of the values were near the lower limit, i.e., low stocking densities prevailed.

Table 4. Descriptive statistics on key variables of the Swiss Agri-Environmental Data Network (SAEDN) dataset. The specification of temporal length (duration) refers to single grazing events. Stocking density refers to the period with grazing cattle. LU = livestock unit.

	Stocking Density (LU/ha)	Grazing Event Duration (days)	Daily Grazing Hours (hours)
Mean	11.1	28.6	12.3
Median	7.0	9.0	11.0
10th percentile	1.4	2.0	6.0
25th percentile	3.2	5.0	8.0
75th percentile	13.3	20.0	14.4
90th percentile	22.1	58.0	24.0
Minimum	0.1	1.0	1.0
Maximum	189	605	24.0
Standard deviation	15.4	59.6	5.7
Coefficient of variation	1.38	2.08	0.47
Skewness	1.75	1.62	0.86

Half of the grazing events lasted more than nine days, and 10% lasted more than about two months (58 days). The distribution of the grazing event duration data was clearly positively skewed, i.e., short grazing periods dominated and long periods of several weeks were rare. This skewness is also clearly evident from the probability density function displayed in Figure 2b. The mean number of daily grazing hours was close to 12 h (Figure 2c), which coincided with the second highest likelihood of occurrence, i.e., farmers frequently pastured their cows for 12 h per day. The multimodal distribution of the daily grazing hours was characterized by an additional peak at 24 h, i.e., the cattle stayed on the pasture throughout the whole day (Figure 2c). These data were slightly positively skewed (skewness = 0.86).

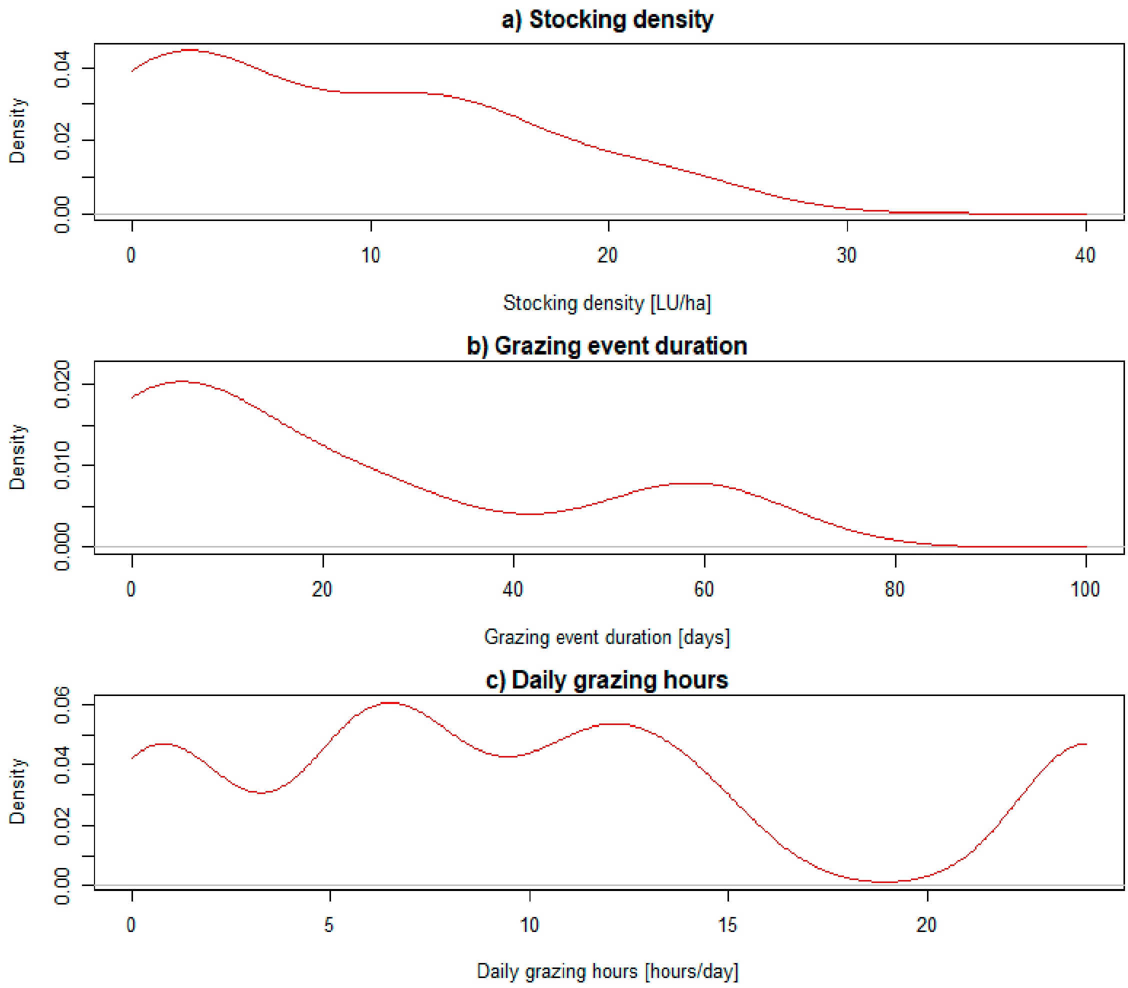

Figure 2. Probability density function for (**a**) stocking density, (**b**) grazing event duration, and (**c**) daily grazing hours. Data source: Swiss Agri-Environmental Data Network (SAEDN), farm data for the period 2011–2014.

3. Results

The plausibility of the new approach was confirmed using the SAEDN dataset in calculations performed per field plot and year, where only farms with complete datasets (and more than one grazing event) were included. The available data allowed 881 assessments for soil compaction caused by grazing cattle at the farm per year level.

Figure 3 displays the distribution of the scaled impact on soil compaction I_{farm} for the valley, hilly, and mountain regions. As can be seen from the diagram, the computed soil compaction at farm level caused by grazing cattle varied greatly between the Swiss farms assessed. This reflects the fact that the grazing intensity differed widely between the farms analyzed. The rank-based nonparametric Kruskal–Wallis H test showed that I_{farm} was close to showing significant differences between the three regions at the 5% level ($p = 0.051$). Visual inspection of Figure 3 shows that the median of I_{farm} in the mountain region was distinctly less negative than the values for the two lower-lying regions, possibly due to the more extensive grazing in the mountain areas than on lower (and often less steep) pastures. In the mountain region, grass yield is also lower; thus, a larger area is needed to graze a specific number of cattle. Nevertheless, a few farms in the mountain region displayed serious soil compaction effects due to grazing cattle (Figure 3, right panel). This may be linked to the fact that mountain farms are mainly dairy farms with frequent grazing, while dairy farms situated in valley and hilly regions with their more favorable climate conditions also devote land to cultivation of crops and vegetables.

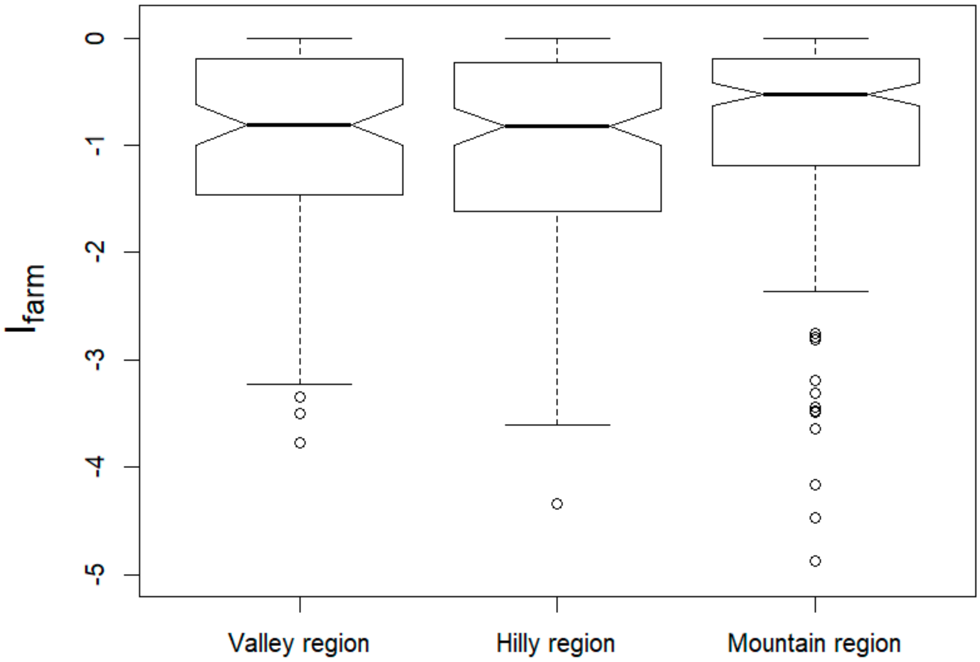

Figure 3. Box plots of scaled impact on compaction *I* (see Equation (4)) at the farm and year level for Swiss farms in valley, hilly, and mountain regions.

Classification of the compaction impacts into the three categories "very unfavorable", "favorable", and "no effect" revealed that 79% of all farms showed no negative effects of grazing activities on aggregate stability, and 64% of all farms showed no negative effects on macropore volume at 10 cm soil depth (Figure 4). However, it also revealed that 20% (aggregate stability) and 32% (macropore volume) of the farms tended to be unfavorably affected by grazing, whereas the percentage with a "very unfavorable" impact was estimated to be much lower. Although no validation data are available, these results can be considered plausible.

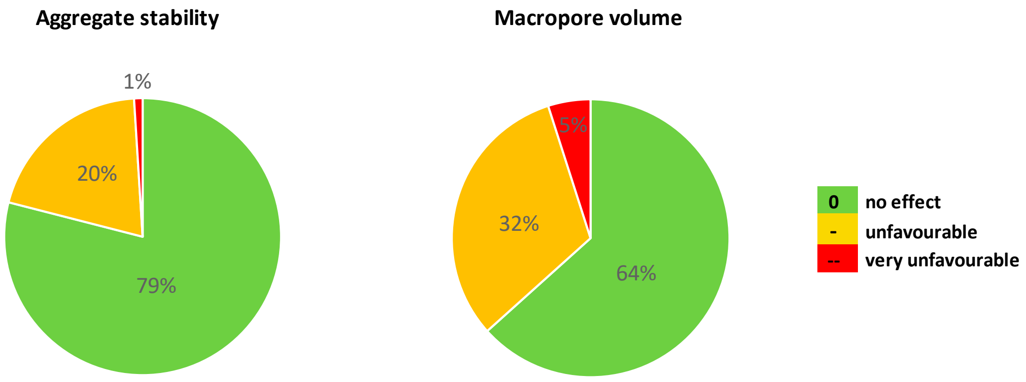

Figure 4. Evaluation of the impact of all grazing events in the test sample on the physical soil indicators "aggregate stability" and "macropore volume" (at 10 cm soil depth) with the new approach for assessing grazing effects on soil compaction. Data source: Swiss Agri-Environmental Data Network (SAEDN), farm data for the period 2011–2014.

To detect the driving model variables for soil compaction caused by trampling cattle, we applied general linear models, with the parameter "impact on soil compaction" (*I*, see Equation (4) as dependent variable. Note that this evaluation was performed at the level of single grazing events k on a specific pasture p. Table 5 lists the set of explanatory (independent) predictor variables that were proposed for the full model shown in Equation (5).

$$I = \beta_0 + \beta_1 \times Reg + \beta_2 \times SoMo + \beta_3 \times AgP + \beta_4 \times StDe + \beta_5 \times GrPe + \beta_6 \times DGH + \varepsilon, \quad (5)$$

where the variable names are as given in Table 5, and ε represents the residuals from the linear regression fit.

The p-values in Table 5 indicate whether the relationship between the response variable I and the independent predictor variables was statistically significant. The explanatory variables fulfilled the condition of sufficiently low multicollinearity because the variation inflation factors (VIF) of all predictor variables amounted to $VIF = 3.5$, a value judged as being unproblematic because a cut-off of $VIF = 5$ is commonly used, and values above $VIF = 10$ indicate too high multicollinearity among the predictor variables [36]. The full model explained 72% of the total variance ($R^2 = 0.72$), while the model ignoring soil moisture and region as predictor variables explained 70% of the total variance ($R^2 = 0.70$). R^2 was derived from the linear fit between the fitted impact I, based on the coefficients provided in Table 5 and the computed values using Equation (4).

Table 5. List of explanatory variables for the full linear model with I as response variable (Equation (5)). SE = standard error; Sign. = statistical significance, *** $p \leq 0.001$, * $p \leq 0.05$; unit1, 1 = valley region, 2 = hilly region, 3 = mountain region; unit2, 1 = dry, 2 = moist, 3 = wet. Soil texture was excluded from the list of explanatory variables as the model accounts for soil type by assuming different monthly soil moisture contents. *StDe* = stocking density; number of LU per area in the period when cattle are actually on pasture (LU/ha).

Explanatory Variable	Unit	Coefficients				
		Mean	SE	*t*-Value	*p* (>*F*)	Sign.
Intercept	-	25.5	1.66	15.3	$<10^{-16}$	***
Region *Reg*	unit1	−1.59	0.48	−2.4	0.015	*
Soil moisture *SoMo*	unit2	−7.76	0.55	−14.1	$<10^{-16}$	***
Area of grazed pasture *AgP*	ha	1.78	0.17	10.7	$<10^{-16}$	***
Stocking density *StDe*	LU/ha	−0.31	0.02	−19.8	$<10^{-16}$	***
Grazing period *GrPe*	days	−0.23	0.03	−8.9	$<10^{-16}$	***
Daily grazing hours *DGH*	hours	−1.19	0.01	−164	$<10^{-16}$	***

Because higher soil compaction impacts are associated with increasingly negative I_{farm} values, negative coefficients in Equation (5) denote that the impact will be higher with increasing values of the respective variable. It is evident from Table 5 and the proposed model approach that soil compaction due to the trampling of grazing cattle increases with increasing number of grazing hours and increasing stocking density. The final regression model, using backward elimination, retained area of grazed pasture, stocking density, and the two variables that determine the total grazing hours of a grazing event (grazing period and daily grazing hours) as highly significant main drivers ($p < 10^{-16}$). Soil moisture was also retained as a highly significant variable in the model. However, the effect of soil moisture was attenuated because the concentration factors for dry and moist soils were assumed to be equal for permanent and temporary meadows (Table 2, “firm soil × dry or moist soil”). Region (valley, hilly, mountain) did not strongly influence the extent of soil compaction ($p < 0.05$), evaluated as compaction effects of single grazing events at the pasture level. This is in line with the findings in Figure 3 which are based on the aggregated impact at the farm level. Soil texture directly affects monthly soil moisture. Here, this relationship was assessed by expert opinion and entered in a look-up table (not shown). The relationship between time of the year (“month”) and soil moisture was fixed for Switzerland.

4. Discussion

We developed a new approach for estimating the extent of soil compaction due to grazing animals based on the soil mechanical method for calculating stress distribution in soils under wheel tracks of agricultural vehicles. We tested the approach using data from several hundred Swiss dairy farms.

The key factors affecting compaction in the new approach are stocking density, duration of grazing period, daily grazing hours, soil moisture, and soil firmness, together with parameters specifying characteristics of the grazing animals (such as weight, hoof/clay dimensions, and daily walking distance). Note that optimizing pasture management for favorable soil structure development (with improvements in vegetation cover or in organic fertilization) is not included in our approach, as it is already incorporated in the overall assessment of soil quality in the model SALCA-SQ [10].

The advantages of this new approach are its physical mechanistic basis, its well-defined set of quantitative input parameters, and the fact that all necessary input parameters can be measured, making the model revisable and systematically improvable. The accuracy of the method can be refined by using measured data for both input and output variables. Because the model parameters are measurable, the model's performance can be scientifically checked. Thus, the approach can be improved systematically as more accurate and complete input data become available. Instead of constant default values, specific information could be used, e.g., precise mean daily walking distances and paths for individual animals based on geographic positioning system (GPS) tracking information.

The model was developed for Swiss conditions, but it can (theoretically) be applied to all grazed pastures worldwide and any farm livestock. However, its primary use is restricted to temperate climate zones, because, in steppe-like ecosystems with often extensive grazing under dry conditions, the impact category indicators "aggregate stability" and "macropore volume" will probably not be affected by grazing cattle. In addition, wet soils are more susceptible to soil physical deterioration by grazing animals. Typical applications of the model are, thus, LCA studies focusing on soil quality on farms with intensive grazing in similar climate conditions as in central Europe. Specific fields of application could be analysis of the effect of different pasture management systems or comparison of the effects of pasturing and mowing on soil physical properties on dairy farms.

The model set-up allows the model to be extended to include further processes, such as accounting for the natural recovery of soil structure compacted by grazing animals in an appropriate way [15]. To test the usefulness of this approach, the relationship between the effects of grazing animals on soil structure (assessed according to our new approach) and the erosion risk in the same landscape could be investigated. This would be especially interesting on the steep slopes of (pre-) alpine pastures [13].

From a methodological point of view, it is advantageous that the approaches for assessing the soil compaction effects caused by wheeling and by trampling can be elaborated in a common mechanistic framework. In addition, the new approach considers the key factors found to be the main drivers of soil structure damage through grazing animals (such as stocking density, animal weight, and soil moisture). Although not explicitly considered in the methodical set-up, the model indirectly takes into account (or assumes) that too heavy stocking rates place excessive pressure on forage plants, reducing plant vigor, frequency, and abundance, thus increasing the frequency of bare patches within the pasture [37]. These bare patches weaken the physical protection afforded by the plant cover with respect to damage by animal hooves on the soil surface [12].

However, it must be pointed out that the new approach is based on a number of assumptions and simplifications. For example, the animals are assumed to trample randomly on the pasture (whereas, in reality, cattle prefer certain areas of the pasture, e.g., close to drinking troughs). Moreover, the slope of the pasture, the length of the period between grazing events, and the relationship between botanical sward composition and soil strength are not considered in the model. Using a linear superposition of the single grazing event impacts for assessment of the total impact may also be a critical assumption, as physical soil processes are often highly non-linear.

Direct validation of the method under natural conditions is not achievable, because it is impossible to exclude concurrent processes with positive impacts on (physical) soil quality, such as stabilization of soil structure by plants and nutrient accumulation through deposition of urine and feces. One option to partly preclude these difficulties (apart from laboratory experiments) may be to measure soil properties of grassland patches with similar site conditions and differing only in their grazing management (e.g., no grazing vs. heavy intensive grazing).

In addition, incomplete information on soil data (see Table 3) may limit the model's performance. However, a multitude of databases are available which contain gridded data for soil texture (see, e.g., https://www.isric.org/explore/soil-geographic-databases) or for soil moisture (see, e.g., https://cds.climate.copernicus.eu/portfolio/dataset/satellite-soil-moisture). For specific small-scale information at the field level, local experts may help to determine the key soil parameters.

5. Conclusions

We present a new, simple, methodologically sound and, therefore, promising tool for estimating the trampling effects of grazing animals on soil compaction. The approach allows the soil compaction effects of different grazing animals to be estimated if their anatomy, weight, movement patterns, and presence on pasture (length of each grazing event, daily grazing hours) are known. In tests, the approach produced plausible results for a sample of several hundred dairy farms in Switzerland.

Because the new approach is based on measurable and quantifiable data, it can be validated by future work using measured data from controlled field experiments. Modules of the new approach, such as the assessment of compaction impact as a consequence of topsoil stress, topsoil strength, and the percentage of trampled area, can be quantitatively refined.

The model's design, its clearly structured processes, and the use of quantifiable input data enable possible future development of single processes. For example, future tracking of animals via GPS would allow for more accurate computation of soil stress, daily walking distance, and percentage of trampled area.

The approach in its current form serves primarily as an analytical tool for researchers. However, with some effort, it could be refined for educational purposes and for planning pasture management, helping farmers to analyze possible effects of changing key impact factors of pasture management (such as daily grazing hours or stocking density) on soil compaction on their pastures.

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