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Assessing the environmental impacts of soil compaction in Life Cycle Assessment

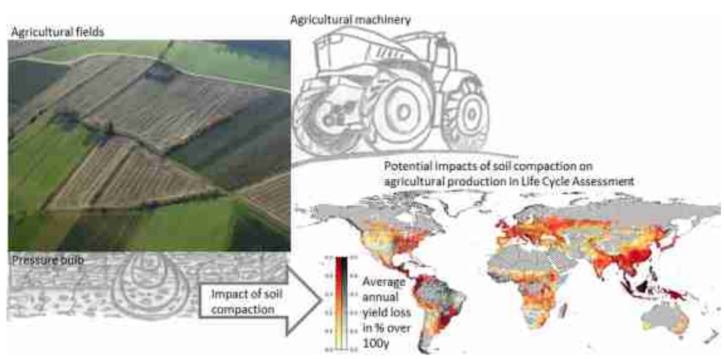
Franziska Stoessel [a,*], Thomas Sonderegger [a], Peter Bayer [b], Stefanie Hellweg [a]

[a] ETH Zurich, Institute of Environmental Engineering, Chair of Ecological Systems Design, John-von-Neumann-Weg 9, CH-8093 Zurich, Switzerland
[b] Technische Hochschule Ingolstadt, Faculty of Mechanical Engineering, Geothermal Energy, Esplanade 10, P.O. Box 21 04 54, D-85049 Ingolstadt, Germany

HIGHLIGHTS

- Presentation of a method to assess soil compaction in Life Cycle Impact Assessment
- Quantification of the soil compaction impact in % yield loss for crop production
- Applicability of the method to various spatial scales and production systems
- Adapting the crop in mechanized systems is effective in reducing compaction impact.
- Vulnerability to compaction impact is highest in moist soil with high clay content.

GRAPHICAL ABSTRACT



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ABSTRACT

Maintaining biotic capacity is of key importance with regard to global food and biomass provision. One reason for productivity loss is soil compaction. In this paper, we use a statistical empirical model to assess long-term yield losses through soil compaction in a regionalized manner, with global coverage and for different agricultural production systems. To facilitate the application of the model, we provide an extensive dataset including crop production data (with 81 crops and corresponding production systems), related machinery application, as well as regionalized soil texture and soil moisture data. Yield loss is modeled for different levels of soil depth (0–25 cm, 25–40 cm and >40 cm depth). This is of particular relevance since compaction in topsoil is classified as reversible in the short term (approximately four years), while recovery of subsoil layers takes much longer. We derive characterization factors quantifying the future average annual yield loss as a fraction of the current yield for 100 years and applicable in Life Cycle Assessment studies of agricultural production. The results show that crops requiring enhanced machinery inputs, such as potatoes, have a major influence on soil compaction and yield losses, while differences between mechanized production systems (organic and integrated production) are small. The spatial variations of soil moisture and clay content are reflected in the results showing global hotspot regions especially susceptible to soil compaction, e.g. the South of Brazil, the Caribbean Islands, Central Africa, and the Maharashtra district of India. The impacts of soil compaction can be substantial, with highest annual yield losses in the range of 0.5% (95% percentile) due to one year of potato production (cumulated over 100 y this corresponds to a one-time loss of 50% of the present yield). These modeling results demonstrate the necessity for including soil compaction effects in Life Cycle Impact Assessment.

* Corresponding author.
E-mail addresses: franziska.stoessel@ifu.baug.ethz.ch (F. Stoessel), sonderegger@ifu.baug.ethz.ch (T. Sonderegger), Peter.Bayer@thi.de (P. Bayer), stefanie.hellweg@ifu.baug.ethz.ch (S. Hellweg).

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1. Introduction

Soil systems have different functions including biomass production, building the physical environment for humans and harboring biodiversity. Moreover, soils are a source of raw material and they store, filter and transform a broad range of substances, such as nutrients (including carbon) and water (McBratney et al., 2011). The fulfilling of these functions depends on a soil's quality (Greiner et al., 2017). Soil quality is characterized by biological, chemical, and physical properties, processes and interactions within the soils. The evaluation of soil quality is not straightforward because governing parameters differ from site to site and depend on the management goal (Karlen et al., 2003). Soil systems are highly heterogeneous. Their consistencies vary horizontally and vertically in space and time. All these aspects represent major challenges in quantifying and comparing impacts of human actions on soil quality worldwide. The importance of soil quality to produce food, fodder, fuel and fabrics was already recognized in the 1980s (Karlen et al., 2003) and it received increased attention within the discussion about how to feed the world's growing population (Bringezu et al., 2014). Stagnation or a decrease in productivity due to soil degradation causes economic loss and affects food security (Bindraban et al., 2012).

Soil degradation is defined as adverse changes in soil properties and processes leading to a reduced capacity of the soil to provide ecosystem functions (Lal et al., 2003). Soil degradation impacts are often long-term and sometimes irreversible (Blume et al., 2010). The main threats to soil are erosion, loss of organic matter, compaction, salinization, landslides, contamination, sealing (European Comission, 2012; Grunewald and Bastian, 2012), soil biodiversity loss, desertification and decline in fertility (Haygarth and Ritz, 2009; Lal, 2009; Lal et al., 2003; Muchena et al., 2005). On a worldwide level, deforestation and agricultural mismanagement are, among others, severe causes of soil degradation (Lal et al., 2003; Muchena et al., 2005). In order to prevent further soil degradation and to restore degraded soils, the European Union harmonized existing soil monitoring networks (Kibblewhite et al., 2008). On the global scale at 1:10 million, GLASOD (Oldeman et al., 1991) was the first assessment on the status of human-induced soil degradation (Sonneveld and Dent, 2009). It was established for policy makers as a basis for priority setting in their action programs. Soil scientists throughout the world gave their expert opinion according to general guidelines on soil degradation in 21 geographic regions (Oldeman et al., 1991). Two categories of degradation processes were assessed. One category contains effects of soil displacement (mainly erosion degradation). The second category estimates soil degradation caused by other physical and chemical deterioration. Despite its limitations, GLASOD remains the only complete, globally consistent information source on land degradation (Gibbs and Salmon, 2015). Rickson et al. (2015) stated that the extent of compacted soil in Europe is 33 million ha. The number has its origin in the soil degradation survey of Oldeman et al. (1991). This corresponds to 18% of Europe's agricultural land, when considering the total agricultural land of the EU28 in 2013 (Eurostat Statistics Explained, 2015). Since the weight of agricultural machinery has increased (Batey, 2009; Hakansson and Reeder, 1994; Kutzbach, 2000; van den Akker, 2004), the problem may even be more pronounced today. Estimates of areas at risk of soil compaction vary. Some authors estimate that 36% of European subsoils have a "high or very high susceptibility" to compaction, other sources report 32% of European soils as being "highly susceptible" and 18% as being "moderately affected" (Jones et al., 2012).

Soil compaction is defined as a "negative" change in the volume shares of the three phases of a soil, i.e. the solid phase, the water and the air-filled spaces. Such a change may be due to compression and/or shearing of the soil pore structure (Blume et al., 2010). The compaction status can be characterized by the relative bulk density, which is the bulk density normalized by laboratory-defined reference states (Hakansson and Lipiec, 2000) or by the penetration resistance (Martínez et al., 2016). Soil compaction affects the function of the pores to store and transport water and gases, nutrients and heat, which is essential for plants and animals to live and grow (Blume et al., 2010). The resulting impact includes the risk of yield reduction, erosion, and reduced water infiltration capacity that may even cause floods after heavy rainfall (Nawaz et al., 2013; Van der Ploeg et al., 2006). In compacted soils, apart from drowning the crops in logged water and disturbed nutrient regimes, microorganisms are not able to work and penetration of agricultural crops' roots is hindered. To make up for yield losses, farmers often apply additional fertilizer to their crops (O'Sullivan and Simota, 1995). Higher fertilizer applications in wet soils cause e.g. more nitrous oxide emissions, which is a highly potent greenhouse gas (Nawaz et al., 2013). Other emissions from fertilization contribute to eutrophication.

Animal trampling and the use of heavy agricultural machinery are the main causes for soil compaction on agricultural land (Bilotta et al., 2007). Wet soils with high clay content and low organic matter are particularly sensitive to impacts of compaction. Clay-organic matter interactions are stabilizing soil aggregates, and to a certain degree, these aggregates are able to absorb the pressure. The stability of the aggregates is weaker in wet soil and the structure is more destroyed at higher pressure (Van der Ploeg et al., 2006). The deeper the compaction occurs in the soil, the less possibility of restoration (Jones et al., 2012). Mechanical deep tillage makes soils even more susceptible for re-compaction after heavy equipment passes over again (Håkansson, 2005; Spoor, 2006).

To implement a better trafficking system, several mechanistic methods are used for the assessment of "soil compaction", e.g. (Biris et al., 2011; Keller et al., 2007; Stettler et al., 2010; van den Akker, 2004). These models are accurate for calculation of the physical impact, such as soil stress versus soil strength for every tire of an agricultural machine at certain environmental conditions. However, they require information on a level of detail that is typically not available to Life Cycle Assessment (LCA) practitioners. Furthermore, the model output often refers to single process steps for the real time management in crop growing without considering entire growing cycles.

Existing Life Cycle Impact Assessment (LCIA) methods related to soil quality are highly heterogeneous (Vidal Legaz et al., 2017). They either provide indicators for soil properties, like soil organic matter (SOM) or soil threats (erosion or desertification etc.). Some methods assess the provision of ecosystem services based on soil functions. Despite methodological improvements, soil quality aspects in LCIA need to be improved (Dijkman et al., 2018). In a previous paper we introduced a framework for consistent LCIA of soil degradation (Stoessel et al., 2016), which we enhanced with further detail in Fig. 1a).

Applications of environmental LCA to evaluate future food systems need to assess a broad variety of environmental impacts in order to avoid burden shifting. The heterogeneity of agricultural production systems and locations has to be taken into account. The goal of this work was to fill the gap in LCIA regarding impacts of soil compaction on a global level with high spatial resolution and being able to assess different agricultural systems. In this paper, we provide an operational method for the assessment of long-term yield reduction due to soil compaction in LCIA. To facilitate the application to agricultural activities, we establish and provide a dataset about machinery use for 81 crops and their growing cycle in various mechanized production systems. This is of particular interest to assess soil quality impact when comparing different production systems like organic and conventional production (Nemecek et al., 2011). Furthermore, this method is applicable on a global, regional or local scale. The global application of the new method and data to the cases of wheat and potato production with a spatial resolution of 1 × 1 km illustrates the extent of potential impact.

2. Materials and methods

2.1. Model overview

We use the empirical model of Arvidsson and Hakansson (1991) to calculate yield loss induced by soil compaction. This model is based on

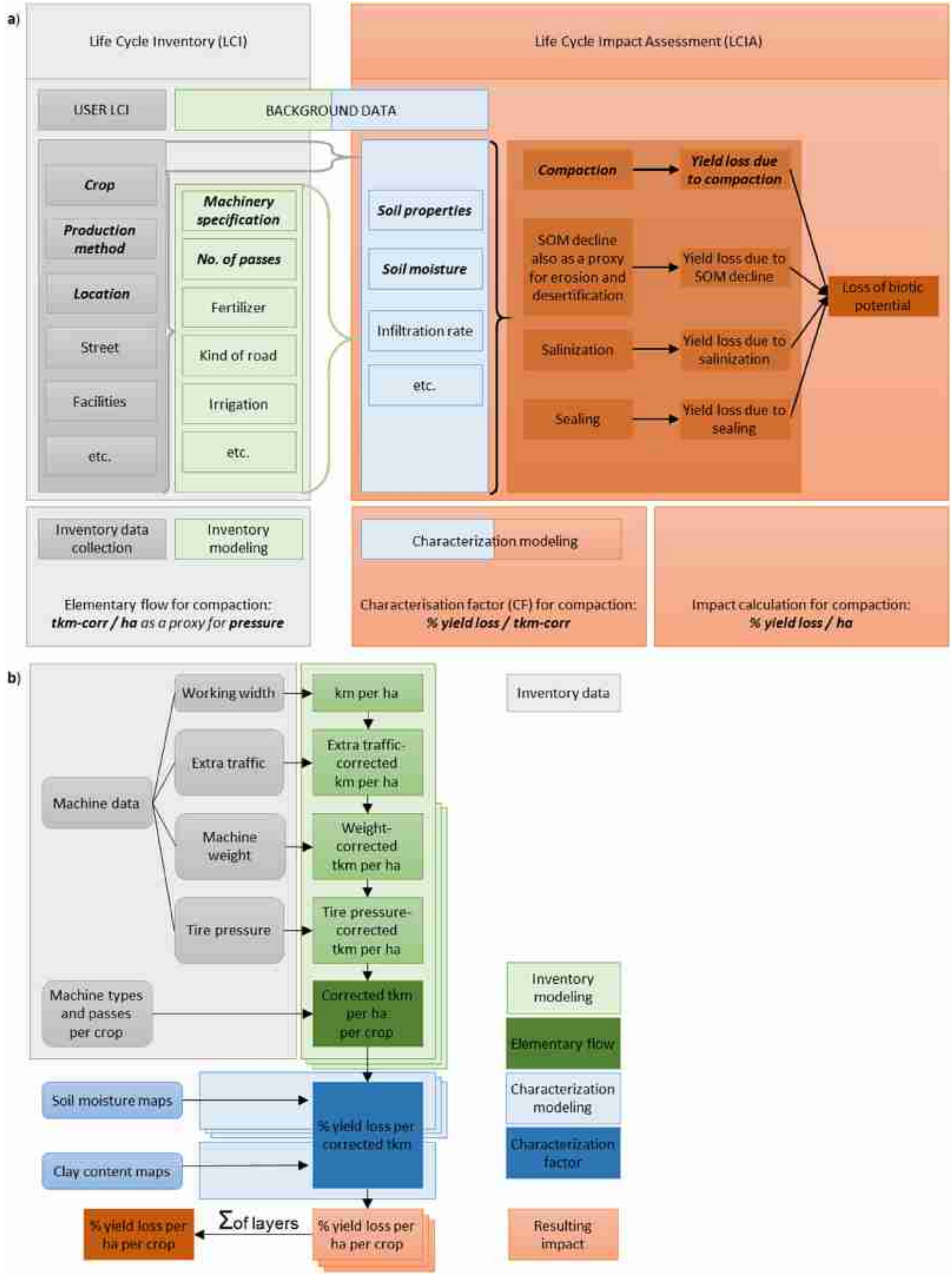

Fig. 1. a) Framework for impacts of soil degradation processes on soil productivity modified from Stoessel et al. (2016). The new impact pathway for agricultural soil compaction is highlighted in bold, italic (SOM: soil organic matter, tkm-corr/ha: corrected tonne-kilometers per ha). b) Detailed modeling approach for soil compaction. Calculation of elementary flows and characterization factors for three soil layers; rounded boxes represent the model input, layered rectangles represent the three soil layers for which separate calculations are made.

a statistical analysis of results obtained from Swedish field trials (Arvidsson and Hakansson, 1996). The applicability is not restricted to Sweden (Lipiec et al., 2003) and an adapted version was successfully tested in Australia for perennial crops (Braunack et al., 2006). The model is relevant to tillage systems that include ploughing. It considers an entire crop growing cycle and the results are calculated for three soil layers (0–25 cm, 25–40 cm and >40 cm depth).

The model input needed is partly crop dependent and partly soil dependent. Crop dependent inputs are machine types and their specifications (i.e. working width, machine weight, and tire pressure), the number of passes per growing cycle and extra traffic on the field (e.g. for turning). Soil dependent inputs are soil moisture and clay content. The data and their origin are shown in Table 1.

With this input, so-called corrected tonne-kilometers per ha (tkm-corr/ha) are calculated, which represent a proxy for the pressure on the soil exerted by the machinery (i.e. the stressor causing soil compaction) during one growing cycle on 1 ha. These values are then translated into a yield loss.

2.2. Model adaptation for LCA: calculation of elementary flows and characterization factors

For our purposes, the model has been separated into two main parts in order to calculate an elementary flow (an exchange between technosphere and biosphere) and a characterization factor to calculate the impact. The crop dependent part, considering machinery data, is used to calculate a proxy elementary flow in corrected tonne-kilometers per ha, representing the cumulated pressure from machinery (technosphere) on the soil (biosphere). In the quantification of characterization factors, soil characteristics are taken into account to calculate spatially resolved characterization factors, translating the elementary flow into damage, measured as yield loss (Fig. 1b). The procedure is described in more detail in the following paragraph.

The distance driven per ha and machine is calculated based on the working width of the machine and a correction for extra traffic (e.g. turns on the head of the field). The result is a corrected distance in km per ha. This distance again is corrected for weight on the different axles of the tractor and trailers and for the tire-pressures, since these factors affect pressure on the soil and the propagation downwards to the deeper soil layers. Accordingly, the corrections are calculated for the three soil layers. Tillage practices and non-tillage practices are treated separately. The corrected tkm/ha for each machine application are multiplied by the number of passes per crop and ha, and these results are summed (separately for each of the three soil layers). The resulting total corrected tkm per ha, crop and layer is the new elementary flow suggested as a proxy for pressure on the soil. Along with productivity information (yield per area), this flow can also be calculated per amount of crop, as typically done in a life cycle inventory (LCI).

In order to calculate the percent yield loss per ha and crop, the corrected tkm per ha are multiplied with an empirically derived factor considering soil moisture and a factor considering the clay content of the soil (the latter is only done for the top soil layer) (Arvidsson and Hakansson, 1991). Both factors combined build the characterization factors for the three soil layers, and they directly translate the corrected tkm per ha into percent yield loss (for each crop and the soil layer).

Topsoil compaction is less persistent than subsoil compaction, which is almost irreversible and very difficult to treat mechanically (Arvidsson, 2001). We adopt the assumption of Arvidsson and Hakansson (1991) that the top soil layer (0–25 cm depth) recovers within 4 years, while the effects of compaction in the mid soil layer (25–40 cm depth) are assumed to persist for 10 years. The model estimates the cumulative yield loss for all years and expresses it in percent of one year's yield (Arvidsson and Hakansson, 1991). The compaction impacts in the bottom soil layer (>40 cm depth) are considered to be permanent (Braunack et al., 2006). In order to aggregate the bottom soil layer impacts with those of the other soil layers, a time horizon of 100 years has been chosen and impacts for one year's yield of the top and mid soil layers are divided by 100 accordingly (Eq. (1)). Results are presented as average annual yield loss (for all layers) in percent of the reference yield without further compaction for all the following crops during the next 100 years.

$$\varnothing annual\ yield\ loss_{100y} = \frac{\%yield\ loss_{top\ soil}}{100y} + \frac{\%yield\ loss_{mid\ soil}}{100y} + {}^{\%yield\ loss_{bottom\ soil}}\!\big/_{y} \quad (1)$$

Since compaction effects showed to be cumulative in previous studies (Braunack et al., 2006), compaction impacts are assumed to be additive. In reality, there is presumably an equilibrium state. An aggregation is useful for common LCA studies, but the method outlined here can also be used without aggregation, if the goal of the study is to model impacts dynamically as a function of time. With regard to the recovery times of 4 years in the top soil layer and 10 years in the mid soil layer, this would mean spreading the model outputs for these layers in a way over the recovery times that the recovery can be approximated by a linear trend. An example is provided in Fig. 2.

2.3. Model input: production and machinery specification data

The choice of specific agricultural machines used in growing crops depends on the crop type, their position in the crop rotation, the production system and other factors. Following the proposal of Stoessel et al. (2016) to reduce the data requirement for the user in LCA, we set up a multi-level calculation system. In this system, the user only needs to provide data on the type of crop, the production system, and the location. The latter is used for selection of the spatially explicit characterization factor that is available in a resolution of 1 km. As shown in Fig. 1a), this information allows for the query of a dataset containing the relevant information on the corresponding default machinery data that is currently provided independent of the location and should be adapted in case of strongly deviating production conditions.

Two distinct datasets were collected to set up this database. First, the machinery used during the entire growing cycle of 81 crops is compiled. This includes the number of passes that every machine does during one growing cycle. In the current version, this is derived from production cost calculation sheets (agridea and FiBL, 2012) for Switzerland. The resulting dataset contains the necessary information on integrated and organic crop production. The key elements that mark the integrated crop growing system are equilibrated nutrient balance, ecological compensation areas on at least 7% of the farm area, diversified crop rotation,

Table 1
Overview of data used in the modeling.

		References
Crop dependent inputs	Machinery use	agridea and FiBL (2012)
	Machine specification	Arvalis (2004), Agrar (2014), Stettler et al. (2010), New Holland (2014), Gazzarin (2016), Maschio (2012), Becker (2014), Holmer (2014), Capaul and Riedi (2012), Michelin (2011), Keller (2005), Diserens et al. (2011), Battiato and Diserens (2013), Diserens (2011), Schjønning et al. (2008), Diserens et al. (2004), Schjonning et al. (2012), Bastgen and Diserens (2009), Diserens (2009), Lamande and Schjonning (2008), BAFU und BLW (2013), Grimme (2014), Claas (2013), Stoessel (2018)
Soil dependent inputs	Soil moisture	Trabucco and Zomer (2010), Siebert et al. (2013), Lüttger et al. (2005)
	Soil clay content	Hengl et al. (2017)

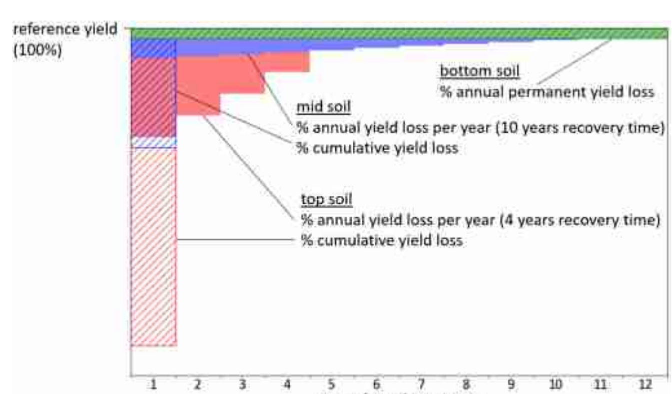

Fig. 2. Dynamic impact modeling with linear recovery, in case of the top soil layer within 4 years, in case of the mid soil layer within 10 years; areas represent yield losses in % of yield in the reference year; hatched: model output, filled: model output assigned to different years with linear recovery, red: top soil layer, blue: mid soil layer, green: bottom soil layer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

soil protection during winter and targeted pest management (Nemecek et al., 2011). Organic growing systems include the key elements of the integrated production systems and in addition - as key characteristics - they do not allow the use of chemically synthesized pesticides and fertilizers and genetically modified organisms. The dataset is presented in Appendix B, and future work can extend it to other crops and production systems.

The second type of dataset comprises the specifications (such as type, weight, working width, or tire inflation pressure) of the different machines in the first dataset. The data sources are given in Table 1. The choice of the agricultural machinery is the most important man-made factor that influences soil compaction, since the wheel load generates the physical pressure on soil. In our dataset, no special efforts to reduce the wheel load, like twin-tires or reduced machine weights, are considered. In future work, the dataset (Appendix C) can be extended to include other machines.

2.4. Model input: soil moisture data

The model requires an estimation of soil moisture content of the topsoil and subsoil layer on a scale from 1 (dry soil) to 5 (wet soil) (Braunack, 1999). Values for the soil stress coefficient from Trabucco and Zomer (2010), ranging from 0 to 1, have been fitted to this scale (and rounded to one decimal place) by Eq. (2) in order to provide a soil moisture content value (SMCV) for the modeling of the characterization factors. This value is used for both soil layers.

$$SMCV = soil\ stress\ coefficient \times 4 + 1 \tag{2}$$

The soil stress coefficient is the ratio of the monthly soil water content (SWC) divided by the maximum SWC, which is the difference between SWC at field capacity and the SWC at the wilting point. This difference is sometimes also referred to as available water capacity (AWC) (Trabucco and Zomer, 2010). Furthermore, irrigation data has been taken into account. The area actually irrigated as a percentage of total area (of a raster cell in a global raster) has been calculated with data from Siebert et al. (2013). It is assumed that soils under irrigation are irrigated up to a soil stress coefficient of 0.5. A value of 0.5 to 0.8 is optimal for plants (Lüttger et al., 2005), corresponding to a soil moisture content value of 3. The final value of the soil moisture content in a raster cell with irrigation is calculated according to Eq. (3), which simply computes the area weighted average of the SMCV and the irrigation value (which is 3).

$$SMCV_{irrigated} = \frac{area_{irrigated}}{area_{total}} \times SMCV + \frac{area_{not\ irrigated}}{area_{total}} \times 3 \tag{3}$$

Soil moisture data at monthly resolution has been run through the model equations and then averaged to a yearly soil moisture correction factor. However, monthly correction factors and hence monthly characterization factors could also be calculated.

2.5. Model input: soil clay content

One of the basic parameters for running the model is the clay content of the top soil layer (Arvidsson and Hakansson, 1991). For our case study, we use datasets from SoilGrids250m (Hengl et al., 2017). This is a global soil information system at 250 m resolution, which is set up by the Institute for World Soil Information (ISRIC). It is based on approximately 110,000 soil profiles from conventional soil surveys and climatic, lithological, biological indices. Among other soil information, it provides global maps of (modeled) clay fractions at seven standard depths. In order to calculate the clay content for the top soil (0–25 cm), the top four layers (0, 5, 15, 30 cm) have been averaged as suggested by Hengl et al. (2017). For compatibility with the spatial data of soil moisture, the clay content data are aggregated to a grid resolution of 1 km using the resample-algorithm of ArcGIS 10.5.

2.6. Method application comparing production systems

The comparison of the modeled inventories allows studying the influence of the crop production system on compaction. This is calculated for 24 pairs of crops in organic and integrated production according to Eq. (4).

$$\Delta_{organic-integrated}\ [\%] = \left(\sum_{crops} \frac{\sum_{layer} tkm_{crop,(organic)} - \sum_{layer} tkm_{crop,(integrated)}}{\sum_{layer} tkm_{crop,(integrated)}} \times 100 \right) / 24 \tag{4}$$

where $\sum_{layer} tkm_{crop,(organic)}$ is the sum of the modeled tkm of one organic crop and for the three layers, and $\sum_{layer} tkm_{crop,(integrated)}$ for integrated production, respectively. The combination of inventory and characterization factors then allows quantifying the magnitude of impact considering both crop and site factors.

3. Results and discussion

3.1. LCI elementary flow

The corrected tonne-kilometers per ha, as a proxy for the pressure on soil that subsequently translates into compaction damage, are on average 16% higher for organic than for integrated crop farming. The same calculation without aggregation of the three soil layers results with an average difference of 17% for the top soil layer, 11% for the mid soil layer, and 24% for the bottom soil layer higher for organic than for integrated crop farming. This is visible in Fig. 3. Fig. 3 also shows for all of the soil layers a)-c) that differences between the crops within one production system are bigger than between the same crops produced in different mechanized production systems.

The differences are partly due to the number of machinery passes during one growing cycle. The average number of passes for the 24 organic and conventional crops considered in this study is 14.2 and 15, respectively. In four cases, the number is higher in organic production systems, in 14 cases lower. The differences in the number of passes result from different fertilizer and pesticide application regimes. Further differences result from the weight and the working widths of the kinds of machines used, especially in the application of farmyard manure in organic systems versus disc spreaders used for synthesized fertilizers and in the mechanical weeding in organic agriculture versus the application of pesticides in conventional farming. Note that we have used one machine specification (i.e. working width, machine weight, and tire pressure) for the same application, e.g. ploughing, in organic and conventional production.

To reduce compaction impact, an appropriate crop choice is more effective than a change between various mechanized production systems. The crops with the highest compaction impacts are potatoes and meadows in their first year. The most prevalent reason for both crops is the number of passes in the fields. Potato production depends highly on the weather conditions and can be intensive in crop protection (weed control and pest management). Moreover, the harvesting procedure needs heavy machines. This is because the harvest of the below-ground growing tubers takes more energy (Williams et al., 2010), which is a direct measure for the size of the machines and the tractor power (Van Linden and Herman, 2014). The corrected tkm per ha for 81 crops are presented for the three soil layers in a table in Appendix E.

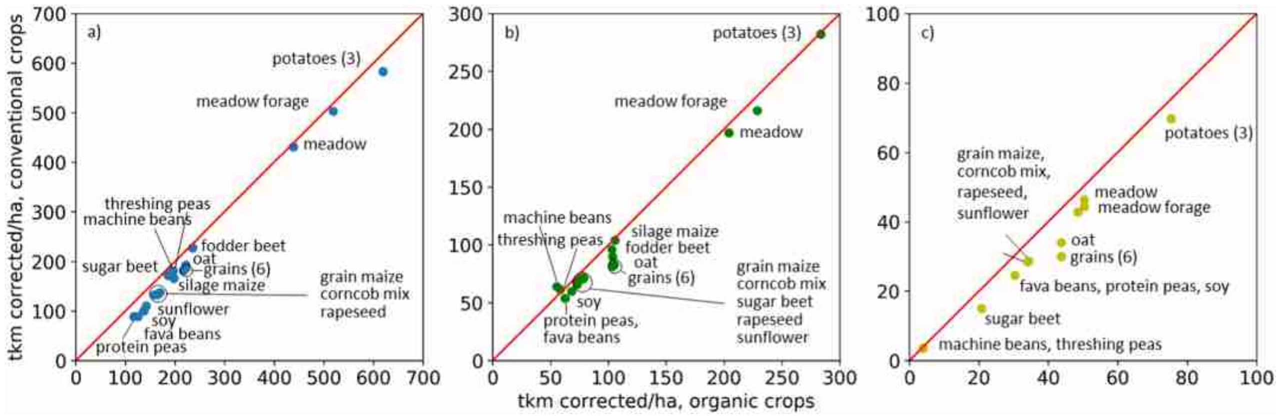

Fig. 3. Comparison of pressure on soil for 24 organic (x-axis) and integrated (y-axis) crops for the three soil layers (a) top soil layer, b) mid soil layer, c) bottom soil layer) (the unit is corrected tkm per ha, which is proportional to the impact for each soil layer at a given site). The line of equality is depicted in red and the number in brackets is the amount of crops and production systems for overlaying dots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. LCIA characterization factors

The characterization factors are expressed in the unit "Percent annual average yield loss per corrected tkm". They depend on soil moisture and (in the case of the top soil layer) on clay content. The high geographical and depth-dependent variation of soil properties requires a high spatial resolution. Characterization factors for the three soil layers (0–25 cm, 25–40 cm and >40 cm depth) are provided as maps (Appendix A, Fig. A1) and as GeoTIFF raster files (for 1 km resolution) on the ETH research collection server. Characterization factors, aggregated to country and sub-country level, are also provided in the Appendix E (for methodological details see also Appendix A, p3).

Regions differ widely in susceptibility to soil compaction. The characterization factors for dry regions, as e.g. North Africa, South Africa, the Arabian Peninsula, the biggest part of Australia, are low. An exception is visible in the Nile Delta where the characterization factors are higher than in its surrounding. This is due to extensive irrigation practices. A similar situation is observed at the foot of the Himalaya Mountains in India.

The influence of the clay content of the soil is apparent when comparing the maps of characterization factors for topsoil and the maps of the characterization factors for bottom- and subsoil. This is especially pronounced in dry regions, e.g. on the Arabian Peninsula, where soil moisture is not responsible for the susceptibility to compaction, but the clay content. The reverse phenomena can be observed in Japan and South East Asia. Both have high soil moisture contents that are reflected in the characterization factors of the bottom and middle soil layer, whereas the characterization factors of the topsoil vary. The topsoil susceptibility of the Japanese islands is lower than the susceptibility of the island of South East Asia due to the lower soil clay content.

Regions with high clay content and high soil moisture and therefore high characterization factors in all soil layers are e.g. the South of Brazil (Santa Catarina, Parana and partly Rio Grande do Sul), the Caribbean Islands, Central Africa, and the Maharashtra district of India.

The characterization factor presented implies a long-term use of the land assessed as agricultural land. However, also if the land were abandoned, compaction impacts would continue showing as a loss of net primary production (NPP). Of course, the assessment would then need to respect recovery times and permanent impacts (see Fig. 2).

3.3. Life cycle impact

The impacts of compaction are illustrated with potato and wheat production for cropping systems in Fig. 4. The same type of figure can be produced for all of the 81 crops with the information provided in the Appendix A–C and the calculation code written in Python™ on Github (link in Appendix A, p2). The geographical distribution of the impacts for both of the crops is very similar (triggered by the characterization factors and their dependence on soil characteristics). The difference of the impact between potato and wheat results from the different machine application during the production in one growing season. Potato cultivation needs more machinery inputs per ha because of the intensive pest management and because of the elaborate harvesting procedure of the belowground tubers (Williams et al., 2010). This is also shown in Lin et al. (2017), where the input of liters of diesel per ha and year is 46 and 104 for winter wheat and potatoes, respectively.

For time series of land use maps, e.g. when modeling dynamically changing crop rotations, the impacts can be aggregated in order to calculate the expected yield reductions. This analysis can go even further by incorporating the effect of changing soil moisture with climate prediction scenarios in order to find optimal crop rotations (land use scenarios).

Moreover, the impact can be assigned to compaction effects from different soil layers. This is shown in the Appendix A, Fig. A2 for the example of potatoes. For regions with a soil moisture class (which is the average of yearly soil moisture) up to 2 (corresponding to a very dry and dry soil), 100% of the impact is assigned to the top soil layer compaction, resulting in a rather short-term effect. In this case, it is assumed that the soil can recover within 4 years if compacting treatments are stopped. When considering all locations with soil moisture class 3–5 (which corresponds to intermediate, moist and wet soil), 61% of the impact is assigned to top soil compaction, 12% to mid soil compaction, and 26% of the impact occurs due to bottom soil compaction. The latter is expected to be permanent.

The potential soil compaction impacts are shown for the whole world, although crop growth is not possible everywhere due to manifold factors and limiting environmental conditions, e.g. temperatures. In the Appendix A, Fig. A3, the impact for the example of potato is shown on the current crop-specific growth area and on present total agricultural area, illustrating current compaction hotspots. However, compared to the status-quo presentation in the Appendix A, Fig. A3, the global coverage of Fig. 4 has the advantage that future sites of crop growth can also be taken into account in order to find out where it is not adequate to expand crop-growing areas with regard to compaction. Insights about potential compaction impacts are also useful when a transition is considered from manually managed small-scale farming system (without significant compaction impacts) to a more mechanized one.

Yield losses due to soil compaction may remain unnoticed since yields underlie year-to-year variations. Farmers often try to compensate yield losses through fertilization or different cultivation practices (Hamza and Anderson, 2005; Nawaz et al., 2013), but by doing so they do not solve the underlying problem of compaction. There are

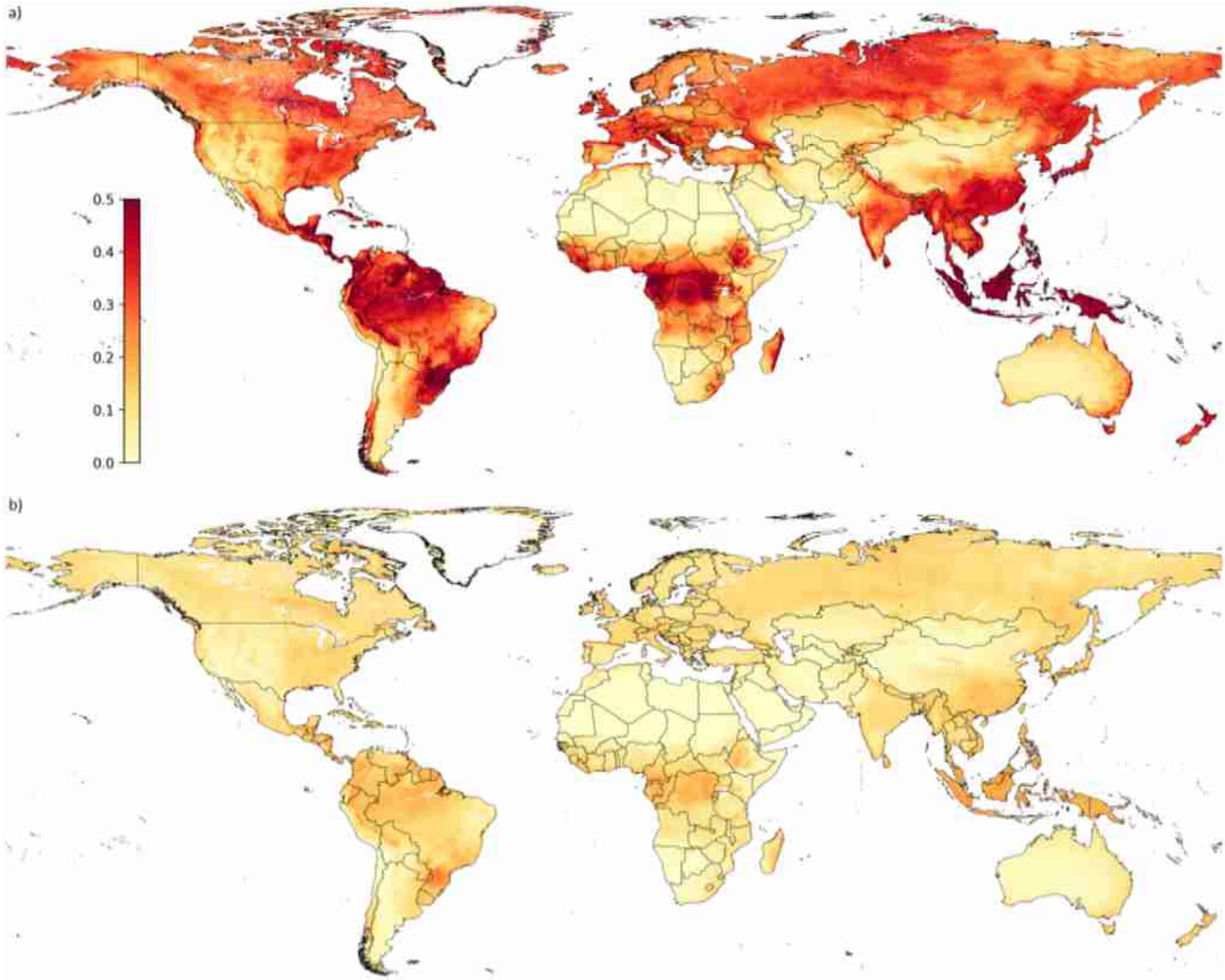

Fig. 4. Comparison of impacts (average annual yield loss in % over 100 years) for potato (integrated, intensive) a) and winter wheat (integrated, intensive) b).

different strategies either to prevent yield loss and other environmental impacts caused by soil compaction or to stimulate recovery in the top and mid soil layers through changed management strategies. Preventative management strategies are e.g. performing field work during low soil moisture periods, twin-tires and reduced tire-pressure for heavy machines (Hamza and Anderson, 2005), ploughing out of the furrow (Chamen et al., 2003), conservation tillage practices (as for example no-till management) (Farooq and Siddique, 2015), adapted crop rotation (ley pasture) (Radford et al., 2007) and controlled traffic farming using permanent traffic lanes (vs. random traffic farming) (Gasso et al., 2013). Furthermore, the enrichment of the soil with soil organic matter (SOM) improves its structure, which might help with mitigating compaction (Hamza and Anderson, 2005; Milà i Canals et al., 2007).

Recovery management strategies (always including preventative management strategies) include actions such as crop rotation change either to loosen compacted layers by a different soil management or by different rooting patterns or to grow crops which are less sensitive to compaction than others (Arvidsson and Hakansson, 2014). The results of recovering by subsoiling (tillage in deep soil layers) are moderate (Batey, 2009).

3.4. Limitations and recommendations for future research

In this study, one particular set of machinery data is used, corresponding to two Swiss production systems. Machinery type and use varies throughout the world and needs to be adapted to the specific conditions. This can either be done by individual data collection or the use of other existing databases, such as the database provided by KTBL (2011–2017). Furthermore, life cycle inventory databases such as ecoinvent (Ecoinvent, 2017) also include data on agricultural machinery. Most of the information needed as model input can be found in ecoinvent process descriptions or reports (Nemecek and Kägi, 2007). Along with the correction factors provided here and basic assumptions on tire pressure, this information can be translated into the elementary flow "corrected tkm per ha", using the referenced Python code (link in Appendix A, p2). A direct integration of compaction pressure flows into the ecoinvent database, by generating the additional elementary flow "corrected tkm per ha" for existing processes, would shortcut the calculations for the user and facilitate the application of the compaction impact assessment method.

To calculate the characterization factors, the original model (Arvidsson and Hakansson, 1991) requires soil moisture data within a scale of 1 to 5 (1 = very dry, 2 = dry, 3 = intermediate, 4 = moist, 5 = wet) (Braunack, 1999). The subjective estimation of these soil moisture classes of the original method was replaced by using soil moisture proxy data from geospatial databases, as described in the Method section. However, it was not possible to distinguish between soil moisture of various soil layers for the whole globe, as required by the selected original model (Arvidsson and Hakansson, 1991). Furthermore, soil moisture does not only vary horizontally and vertically, but also in time. Therefore, it is suggested to consider soil moisture data at monthly or daily resolution for calculation of temporally differentiated characterization factors in future work. Since crop production is also season-dependent and varies in time from North to South, inventory modeling should be temporally differentiated as well and combined with the corresponding characterization factors to increase the reliability of the results, as done for water consumption impacts (Pfister and Bayer, 2014).

The model is an empirical model, which could be seen as a limitation since it is a black box. However, the model has been proven to work for different conditions (Braunack et al., 2006). The model is suitable for annual crops grown in moldboard ploughing crop systems that is applied in approximately 90% of the global arable area. This is 100% minus the estimated area under conservation tillage (7.4–11%), which has the tendency to rise (Derpsch et al., 2010; Kassam et al., 2014; Lal, 2013). Conservation tillage includes no-till systems where soils are not disturbed through tillage. An extension for conservation tillage systems and for perennial crops, as it was done by Braunack et al. (2006), would complete the possibilities for analyses, especially for the analysis of crop rotations with different tillage systems.

Soil compaction is not only a problem of crop growing agriculture. Soil compaction also occurs on pastures caused by grazing animals (Drewry et al., 2008), in forest harvesting, in recreation land use, and construction sites (Batey, 2009). The environmental assessment of a product or service requires including all stages of a life cycle. It is thus desirable to include other sources of soil compaction in the future.

Since GLASOD is the only global map on soil degradation that includes soil compaction, it is difficult to validate the results presented above. For single regions, more detailed and more up to date maps are available and presented for Europe in the Appendix A, Fig. A4. A visual comparison of the characterization factors for top soil with the map reveals a good accordance of the regions associated with compaction risks.

4. Conclusions

This study offers a new method for LCA practitioners to include impact assessment of soil compaction into Life Cycle Assessment of agricultural products. It enables the calculation of potential compaction impacts of crop rotation and cropland expansion scenarios. This type of analysis can be especially interesting in combination with climate change and future land-use scenarios, for example.

The comparison of the elementary flows of 24 pairs of organic and conventional crops revealed that the differences in impacts of mechanized production systems are small when compared with differences in impacts of different crops. Thus, to avoid compaction impacts, crop choice has the larger leverage than changing from one production method to another. Furthermore, an appropriate timing of the machinery application to favorable soil conditions (low soil moisture) and reducing the machinery load are effective measures to reduce compaction impacts.

The structures of the soils vary widely. In this study, the global characterization factors for the impact of soil compaction were based on spatially highly resolved soil clay data (250 m, aggregated to 1 km) and soil moisture data at a resolution of 1 km. The characterization factors for dry regions are low, except in regions where widespread irrigation is practiced. The influence of the clay content of a soil is reflected in the characterization factors for the topsoil. Dry sites with enhanced clay content have higher values for the characterization factors in the topsoil than for the characterization factors in the middle and bottom soil. The highest characterization factors for all soil layers are observed in regions with high soil moisture and high values of clay content. In those regions, annual yield losses averaged over 100 years can amount up to 0.5% (cumulated over 100 y this corresponds to a one-time loss of 50% of the present yield), and, hence, at those locations compaction represents a substantial risk to agricultural production.

The geographical distribution of the characterization factors is clearly visible in the impact of different crop productions under the assumption that the elementary flow for one crop is the same worldwide. Around one quarter of the impact in regions with soil moisture classes 3–5 (that corresponds to intermediate, moist and wet soils) is attributed to compaction impacts resulting from bottom soil compactions, which are expected to be permanent. Repeated crop growing under unfavorable conditions can accumulate the compaction impact and harm the production of agricultural commodities for a long time.

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Supplementary data

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References

Agrar, 2014. Mistral, Stallmiststreuer. GVS Agrar AG, Land- und Kommunalmaschinen, Im Majorenacker 11, CH-8207 Schaffhausen Tel. +41 (0)52 631 19 00, info@gvs-agrar.ch, www.gvs-agrar.ch, Schaffhausen.

agridea, FiBL, 2012. Deckungsbeiträge: Getreide, Hackfrüchte, Übrige Ackerkulturen, Futterbau, Spezialkulturen, Tierhaltung, Agrotourismus. AGRIDEA Lindau, AGRIDEA Lausanne.

Arvalis, 2004. Choisir ses outils: du travail du sol à la récolte. Arvalis - Institut du Végétal (France), Paris.

Arvidsson, J., 2001. Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden - I. Soil physical properties and crop yield in six field experiments. Soil Tillage Res. 60, 67–78.

Arvidsson, J., Hakansson, I., 1991. A model for estimating crop yield losses caused by soil compaction. Soil Tillage Res. 20, 319–332.

Arvidsson, J., Hakansson, I., 1996. Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. Soil Tillage Res. 39, 175–197.

Arvidsson, J., Hakansson, I., 2014. Response of different crops to soil compaction-short-term effects in Swedish field experiments. Soil Tillage Res. 138, 56–63.

BAFU, BLW, 2013. Bodenschutz in der Landwirtschaft: Ein Modul der Vollzugshilfe Umweltschutz in der Landwirtschaft. Bundesamt für Umwelt (BAFU), Bundesamt für Landwirtschaft (BLW), Bern, p. 59.

Bastgen, H.M., Diserens, E., 2009. q Value for calculation of pressure propagation in arable soils taking topsoil stability into account. Soil Tillage Res. 102, 138–143.

Batey, T., 2009. Soil compaction and soil management - a review. Soil Use Manag. 25, 335–345.

Battiato, A., Diserens, E., 2013. Influence of Tyre Inflation Pressure and Wheel Load on the Traction Performance of a 65 kW MFWD Tractor on a Cohesive Soil. Vol. 5.

Becker, 2014. In: Becker Landtechnik Oberweser T (Ed.), Dreipunktmontiertes Saatbettkulturgerät mit vibrierenden Federzinken mail@becker-lt.de, www.kongskilde.com, editor, Oberweser.

Bilotta, G.S., Brazier, R.E., Haygarth, P.M., 2007. The impacts of grazing animals on the quality of soils, vegetation, and surface waters in intensively managed grasslands. Adv. Agron. 94, 237–280.

Bindraban, P.S., van der Velde, M., Ye, L.M., van den Berg, M., Materechera, S., Kiba, D.I., et al., 2012. Assessing the impact of soil degradation on food production. Curr. Opin. Environ. Sustain. 4, 478–488.

Biris, S.S., Ungureanu, N., Maican, E., Murad, E., Vladut, V., 2011. Fem Model to Study the Influence of Tire Pressure on Agricultural Tractor Wheel Deformations, Jelgava. pp. 223–228.

Blume, H.-P., Brümmer, G.W., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., et al., 2010. Scheffer/Schachtschabel: Lehrbuch der Bodenkunde. Spektrum Akademischer Verlag.

Braunack, M., 1999. SRDC Final Report - Project BS142S: Economic Cost of Soil Compaction. Bureau of Sugar Experiment Stations Queensland, Australia:p. 24 http://elibrary.sugarresearch.com.au/.

Braunack, M.V., Arvidsson, J., Hakansson, I., 2006. Effect of harvest traffic position on soil conditions and sugarcane (Saccharum officinarum) response to environmental conditions in Queensland, Australia. Soil Tillage Res. 89, 103–121.

Bringezu, S., Schütz, H., Pengue, W., O'Brien, M., Garcia, F., Sims, R., et al., 2014. Assessing global land use: balancing consumption with sustainable supply. In: International Resource Panel WGoLaS (Ed.), A Report of the Working Group on Land and Soils of the International Resource Panel. UNEP.

Capaul, G.A., Riedi, B., 2012. Landwirtschaftliches Handbuch zum Wirz-Kalender. Verlag Wirz, Basel.
Chamen, T., Alakukku, L., Pires, S., Sommer, C., Spoor, G., Tijink, F., et al., 2003. Prevention strategies for field traffic-induced subsoil compaction: a review part 2. Equipment and field practices. Soil Tillage Res. 73, 161–174.
Claas, 2013. In: claas.de (Ed.), ROLLANT 350 RC 3 4 0 RF, Ausgereift. Robust. ROLLANT stark. CLAAS Vertriebsgesellschaft GmbH H Tel. +49 (0)52 47 12 - 1144.
Derpsch, R., Friedrich, T., Kassam, A., Li, H.W., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. Int. J. Agric. Biol. Eng. 3.
Dijkman, T.J., Basset-Mens, C., Antón, A., Núñez, M., 2018. LCA of food and agriculture. In: Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds.), Life Cycle Assessment: Theory and Practice. Springer International Publishing, Cham, pp. 723–754.
Diserens, E., 2009. Calculating the contact area of trailer tyres in the field. Soil Tillage Res. 103, 302–309.
Diserens, E., 2011. Bodengerechter Maschineneinsatz bei der Gemüseernte. Der Gemüsebau/Le Maraicher. Agroscope, Tänikon.
Diserens, E., Spless, E., Steinmann, G., 2004. TASC: a new practical tool to prevent soil compaction damage in arable farming. TASC: Eine PC-Anwendung zur Prävention von schadverdichtungen im aciterbau, pp. 363–369.
Diserens, E., Defossez, P., Duboisset, A., Alaoui, A., 2011. Prediction of the contact area of agricultural traction tyres on firm soil. Biosyst. Eng. 110, 73–82.
Drewry, J.J., Cameron, K.C., Buchan, G.D., 2008. Pasture yield and soil physical property responses to soil compaction from treading and grazing - a review. Aust. J. Soil Res. 46, 237–256.
Ecoinvent, Ecoinvent (Eds.), 2017. Ecoinvent - The World's Most Consistent & Transparent Life Cycle Inventory Database. ETH, Agroscope, EMPA, EPFL, PSI, Zurich.
European Comission, 2012. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The Implementation of the Soil Thematic Strategy and Ongoing Activities. European Comission.
Eurostat Statistics Explained, 2015. Farm Structure Statistics. 2017.
Farooq, M., Siddique, K., 2015. Conservation Agriculture. Springer International Publishing.
Gasso, V., Sorensen, C.A.G., Oudshoorn, F.W., Green, O., 2013. Controlled traffic farming: a review of the environmental impacts. Eur. J. Agron. 48, 66–73.
Gazzarin, C., 2016. Maschinenkosten 2016. Agroscope Transfer. 142. Agroscope, Tänikon, Switzerland.
Gibbs, H.K., Salmon, J.M., 2015. Mapping the world's degraded lands. Appl. Geogr. 57, 12–21.
Greiner, L., Keller, A., Grêt-Regamey, A., Papritz, A., 2017. Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services. Land Use Policy 69, 224–237.
Grimme, 2014. SE 75/85-55, 1-reihige, seitengezogene Kartoffelvollerntemaschine, mit Großbunker. Grimme Landmaschinenfabrik GmbH & Co. KG HSD-D Telefon +49 5491 666-0, Telefax +49 5491 666-2298, grimme@grimme.de, www.grimme.de, editor.
Grunewald, K., Bastian, O., 2012. Ökosystemdienstleistungen: Konzept, Methoden und Fallbeispiele. Springer Spectrum.
Håkansson, I., 2005. Machinery-induced compaction of arable soils: incidence - consequences - counter-measures. Reports From the Division of Soil Management. Department of Soil Sciences Uppsala, Uppsala, p. 158.
Hakansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res. 53, 71–85.
Hakansson, I., Reeder, R.C., 1994. Subsoil compaction by vehicles with high axle load extent, persistence and crop response. Soil Tillage Res. 29, 277–304.
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems - a review of the nature, causes and possible solutions. Soil Tillage Res. 82, 121–145.
Haygarth, P.M., Ritz, K., 2009. The future of soils and land use in the UK: soil systems for the provision of land-based ecosystem services. Land Use Policy 26, S187–S197.
Hengl, T., Mendes de Jesus, J., Heuvelink, G.B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotic, A., et al., 2017. SoilGrids250m: global gridded soil information based on machine learning. PLoS One 12, e0169748.
Holmer, 2014. Terra Dos T4-40. Holmer Maschinenbau GmbH r, 84069 Schierling/Eggmühl info@holmer-maschinenbau.com, editor.
Jones, A., Panagos, P., Barcelo, S., Bouraoui, F., Bosco, C., Dewitte, O., et al., 2012. The State of Soil in Europe. European Union.
Karlen, D.L., Ditzler, C.A., Andrews, S.S., 2003. Soil quality: why and how? Geoderma 114, 145–156.
Kassam, A., Li, H.W., Niino, Y., Friedrich, T., Jin, H., Wang, X.L., 2014. Current status, prospect and policy and institutional support for conservation agriculture in the Asia-Pacific region. Int. J. Agric. Biol. Eng. 7, 1–13.
Keller, T., 2005. A model for the prediction of the contact area and the distribution of vertical stress below agricultural tyres from readily available tyre parameters. Biosyst. Eng. 92, 85–96.
Keller, T., Defossez, P., Weisskopf, P., Arvidsson, J., Richard, G., 2007. SoilFlex: a model for prediction of soil stresses and soil compaction due to agricultural field traffic including a synthesis of analytical approaches. Soil Tillage Res. 93, 391–411.
Kibblewhite, M.G., Jones, R.J.A., Montanarella, L., Baritz, R., Huber, S., Arrouays, D., et al., 2008. Environmental assessment of soil for monitoring volume VI: soil monitoring system for Europe. JRC Scientific and Technical Reports. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra, p. 88.
KTBL, (KTBL) KfTuBidLeV (Eds.), 2011–2017. Verfahrenrechner Pflanze. KTBL www.ktbl.de.
Kutzbach, D.H., 2000. Trends in power and machinery. J. Agric. Eng. Res. 76, 237–247.
Lal, R., 2009. Soils and food sufficiency. A review. Agron. Sustain. Dev. 29, 113–133.
Lal, R., 2013. Enhancing ecosystem services with no-till. Renewable Agric. Food Syst. 28, 102–114.
Lal, R., Sobecki, T.M., Iivari, T., Kimble, J.M., 2003. Soil degradation. Soil Degradation in the United States: Extent, Severity, and Trends. Lewis Publishers, CRC Press, p. 224.
Lamande, M., Schjonning, P., 2008. The ability of agricultural tyres to distribute the wheel load at the soil-tyre interface. J. Terramech. 45, 109–120.
Lin, H.-C., Huber, J.A., Gerl, G., Hülsbergen, K.-J., 2017. Effects of changing farm management and farm structure on energy balance and energy-use efficiency—a case study of organic and conventional farming systems in southern Germany. Eur. J. Agron. 82, 242–253.
Lipiec, J., Arvidsson, J., Murer, E., 2003. Review of modelling crop growth, movement of water and chemicals in relation to topsoil and subsoil compaction. Soil Tillage Res. 73, 15–29.
Lüttger, A., Dittmann, B., Sourell, H., 2005. Leitfaden zur Beregnung landwirtschaftlicher Kulturen. Landesamt für Verbraucherschutz, Landwirtschaft und Flurneuordnung.
Martínez, I., Chervet, A., Weisskopf, P., Sturny, W.G., Etana, A., Stettler, M., et al., 2016. Two decades of no-till in the Oberacker long-term field experiment: part I. Crop yield, soil organic carbon and nutrient distribution in the soil profile. Soil Tillage Res. 163, 141–151.
Maschio, GmbH MD (Eds.), 2012. Aus Liebe zum Boden. Kreiseleggen. Maschio Deutschland GmbH, Äußere Nürnberger Str. 5, 91177 Thalmässing Tel.: 0 91 73-79 00-0, E-Mail: dialog@maschio.de, www.maschio.de.
McBratney, A., Wheeler, I., Malone, B., Minasny, B., 2011. Soil Carbon Mapping and Life Cycle Analysis. Ecotech & Tools, Montpellier.
Michelin, 2011. Miltibib(TM): The Wider Choice for Multipurpose Medium and High Horsepower Tractors and Other Applications. Michelin AG.
Milà i Canals, L., Romanyà, J., Cowell, S.J., 2007. Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA). J. Clean. Prod. 15, 1426–1440.
Muchena, F.N., Onduru, D.D., Gachini, G.N., de Jager, A., 2005. Turning the tides of soil degradation in Africa: capturing the reality and exploring opportunities. Land Use Policy 22, 23–31.
Nawaz, M.F., Bourrie, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron. Sustain. Dev. 33, 291–309.
Nemecek, T., Kägi, T., 2007. Life cycle inventories of agricultural production systems: data v2.0 (2007). ecoinvent Report No. 15. ecoinvent Centre: Swiss Center for Life Cycle Inventories, Zürich and Dübendorf.
Nemecek, T., Dubois, D., Huguenin-Elie, O., Gaillard, G., 2011. Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agric. Syst. 104, 217–232.
New Holland, 2014. New-Holland-Grossballenpresse Modell BB920. Holland N.
Oldeman, L.R., Hakkeling, R.T.A., Sombroek, W.G., 1991. World map of the status of human-induced soil degradation. In: UN IWSC-I-F-Iicw (Ed.), An Explanatory Note, Global Assessment of Soil Degradation GLASOD.
O'Sullivan, M.F., Simota, C., 1995. Modelling the environmental impacts of soil compaction: a review. Soil Tillage Res. 35, 69–84.
Pfister, S., Bayer, P., 2014. Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production. J. Clean. Prod. 73, 52–62.
Radford, B.J., Yule, D.F., McGarry, D., Playford, C., 2007. Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. Soil Tillage Res. 97, 249–255.
Rickson, R.J., Deeks, L.K., Graves, A., Harris, J.A.H., Kibblewhite, M.G., Sakrabani, R., 2015. Input constraints to food production: the impact of soil degradation. Food Sec. 7, 351–364.
Schjønning, P., Lamandé, M., Tøgersen, F.A., Arvidsson, J., Keller, T., 2008. Modelling effects of tyre inflation pressure on the stress distribution near the soil–tyre interface. Biosyst. Eng. 99, 119–133.
Schjonning, P., Lamandé, M., Keller, T., Pedersen, J., Stettler, M., 2012. Rules of thumb for minimizing subsoil compaction. Soil Use Manag. 28, 378–393.
Siebert, S., Henrich, V., Frenken, K., Burke, J., 2013. In: Rheinische Friedrich-Wilhelms-University B, Germany, Aquastat FaAOotUN, Rome, Italy (Eds.), Global Map of Irrigation Areas Version 5. Food and Agriculture Organization of the United Nations (FAO) AQUASTAT website.
Sonneveld, B.G., Dent, D.L., 2009. How good is GLASOD? J. Environ. Manag. 90, 274–283.
Spoor, G., 2006. Alleviation of soil compaction: requirements, equipment and techniques. Soil Use Manag. 22, 113–122.
Stettler, M., Keller, T., Schjønning, P., Lamandé, M., Lassen, P., Pedersen, J., et al., 2010. Terranimo® - A Web-Based Tool for Assessment of the Risk of Soil Compaction Due to Agricultural Field Traffic. p. 384.
Stoessel, F., 2018. Collection of Online-References for Machinery Specification Data. 2018.
Stoessel, F., Bachmann, D., Hellweg, S., 2016. In: Holden, N. (Ed.), Assessing the Environmental Impacts of Agricultural Production on Soil in a Global Life Cycle Impact Assessment Method: A Framework. LCA Food 2016, Dublin, pp. 372–379.
Trabucco, A., Zomer, R.J., 2010. Global soil water balance geospatial database. 2017. CGIAR Consortium for Spatial Information. CGIAR-CSI GeoPortal.
van den Akker, J.J.H., 2004. SOCOMO: a soil compaction model to calculate soil stresses and the subsoil carrying capacity. Soil Tillage Res. 79, 113–127.
Van der Ploeg, R.R., Ehlers, W., Horn, R., 2006. Schwerlast auf dem Acker. Spektrum der Wissenschaft, pp. 80–88.
Van Linden, V., Herman, L., 2014. A fuel consumption model for off-road use of mobile machinery in agriculture. Energy 77, 880–889.
Vidal Legaz, B., Maia De Souza, D., Teixeira, R.F.M., Antón, A., Putman, B., Sala, S., 2017. Soil quality, properties, and functions in life cycle assessment: an evaluation of models. J. Clean. Prod. 140, 502–515.
Williams, A.G., Audsley, E., Sandars, D.L., 2010. Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. Int. J. Life Cycle Assess. 15, 855–868.