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Assessing the environmental impacts of soil compaction in Life Cycle Assessment

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Abstract

Maintaining the biotic capacity of soil productivity is of key importance with regard to global food and biomass provision. One driver of 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 system), related machinery application, as well as regionalized soil texture and soil moisture data. The yield loss is modeled for different levels of soil depth. This is of particular relevance since the compaction in topsoil is classified as reversible in the short term (approximately four years), while recovery of the subsoil layers takes much longer. The final characterization factors quantify the future average annual yield loss as a fraction of current yield for 100 years. The results show that crop type, soil texture and soil moisture have a major influence on soil compaction and yield losses, while differences between mechanized production systems (organic and integrated production) are small. The impacts of soil compaction can be substantial, with highest annual yield losses for the next 100 y crop production in

the range of 0.5% (95% percentile) due to one year of potato production. These modeling results demonstrate the necessity for including soil compaction effects in Life Cycle Impact Assessment.

Keywords

Soil compaction; Soil degradation; Yield loss; Agricultural production; Life cycle impact assessment

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. Soil quality is controlled by a range of biological, chemical or physical parameters and none of these parameters are sufficient as a standalone indicator for evaluating soil quality (Karlen et al., 2003b). Soil systems are highly heterogeneous. Their consistencies vary horizontally and vertically in space and they are composed of minerals, organic material, gases, liquids and living organisms. The value of a soil parameter might be positive for soil quality on one site, but the same value may be negative at another site (Karlen et al., 2003a). All these aspects represent major challenges in quantifying impacts of human actions on soil quality worldwide.

The importance of good soil quality to produce food, fodder, fuel and fabrics was already recognized in the 1980s (Karlen et al., 2003b) 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 means adverse changes in soil properties leading to a reduced capacity to function (Lal et al., 2003). Soil degradation impacts are often long-term and sometimes irreversible (Blume et al., 2010). The main threats to soil are soil erosion, loss of soil organic matter, soil compaction, salinization, landslides, soil contamination, soil sealing (European Comission, 2012; Grunewald and Bastian, 2012) soil biodiversity loss, desertification and decline in soil fertility (Haygarth and Ritz, 2009; Lal, 2009; Lal et al., 2003; Muchena et al., 2005). On a worldwide level, agricultural mismanagement, deforestation and overexploitation of vegetation for domestic and industrial use are 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).

In Life Cycle Assessment (LCA) only some indicators address soil quality or soil degradation (Garrigues et al., 2012; Stoessel et al., 2016). There is widespread recognition that more comprehensive indicators are needed to assess all major drivers of soil quality loss (Baitz, 2007; Blonk et al., 1997; Milà i Canals et al., 2007a). The barriers, which have prevented such development, include the complexity and diversity of soils. In a previous paper (Stoessel et al., 2016) we introduced a framework for consistent Life Cycle Impact Assessment (LCIA) of soil degradation. In the current paper, we present a model for the impact pathway of soil compaction, which is embedded (in bold, italic) into the framework of Figure 1.

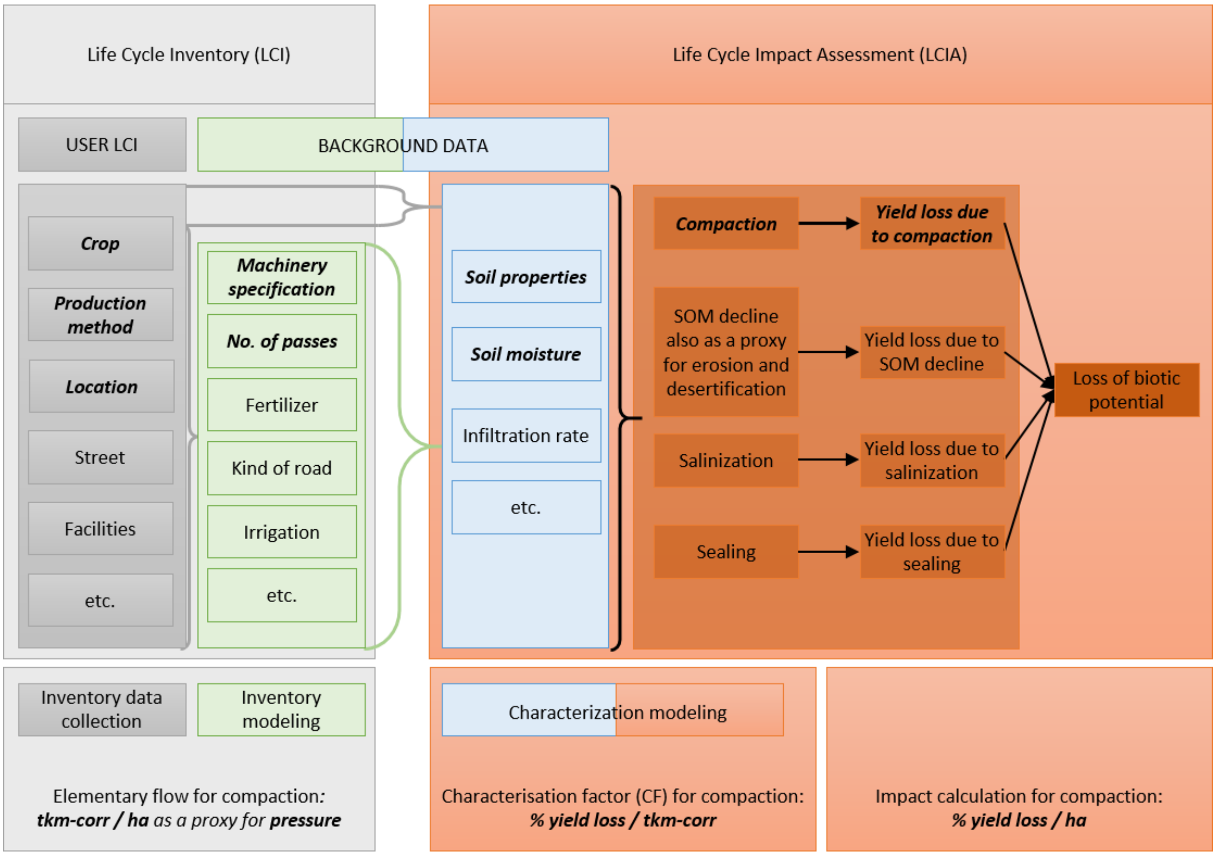

Figure 1: Impact pathway of soil degradation processes on soil productivity adapted from Stoessel et al. (2016). The new impact pathway for agricultural soil compaction is highlighted in bold, italic (SOM: soil organic matter, tkm-corr/ha: corrected tonne-kilometers per ha).

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. The structure of the solid phase with the water and air filled spaces in between is called matrix. The volume share of the water and air filled spaces is dependent on the content of organic matter and the pedogenesis. A change of the matrix may be due to compression and/or a shearing of the soil pore structure (Blume et al., 2010). The compaction status of the matrix can be characterized by the relative bulk density, which is the bulk density normalized by laboratory-defined reference states (Håkansson and Lipiec, 2000).

Animal trampling and the use of heavy agricultural machines 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).

Rickson et al. (2015) stated that the extent of compacted soil in Europe is 33 million hectares which corresponds to 18% of Europe's agricultural land, when considering the total agricultural land of the EU28 in 2013 (Eurostat Statistics Explained, 2015). The number has its origin in the soil degradation survey of Oldeman et al. (1991). Since then, the weight of agricultural machinery has further increased (Håkansson and Reeder, 1994; van den Akker, 2004) and thus, 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 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 impacts include risk of yield reduction, water erosion and greenhouse gas emissions (Nawaz et al., 2013; Van der Ploeg et al., 2006). In compacted soils, apart from drowning the crops in logged water, nutrient regimes may also be affected due to disturbed water and air transports. Microorganisms are not able to work and penetration of agricultural crops' roots is hindered. To make up for this effect, farmers often apply additional fertilizer to their crops. Higher fertilizer applications (especially nitrogen) in wet soils cause more nitrous oxide emissions, which is a highly potent greenhouse gas (Nawaz et al., 2013). Compacted soils are less capable of storing water, which results in water erosion and may even cause floods after heavy rainfall.

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). Currently, the only measures against soil compaction are a restriction of axle and total load and conducting fieldwork only during dry conditions. Similar measures are implemented for road transport and earthworks in the construction sector (Van der Ploeg et al., 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 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.

In this paper, we provide a 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 a range of crops and their growing cycle in various mechanized production systems. The application of the new method and data to the cases of wheat and potato production illustrates the extent of impact. Along with this paper, the data and the calculation code written in Python™ are published with the necessary instructions to use the model (link to the Github is given in the in the Supplementary Information Appendix A, p2).

2. Materials and Methods

2.1. Model Overview

We use the empirical model of Arvidsson and Håkansson (1991) to calculate yield loss induced by soil compaction. This model is based on a statistical analysis of results obtained from Swedish field trials (Arvidsson and Håkansson, 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. 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 one ha. These values are then translated into a yield loss.

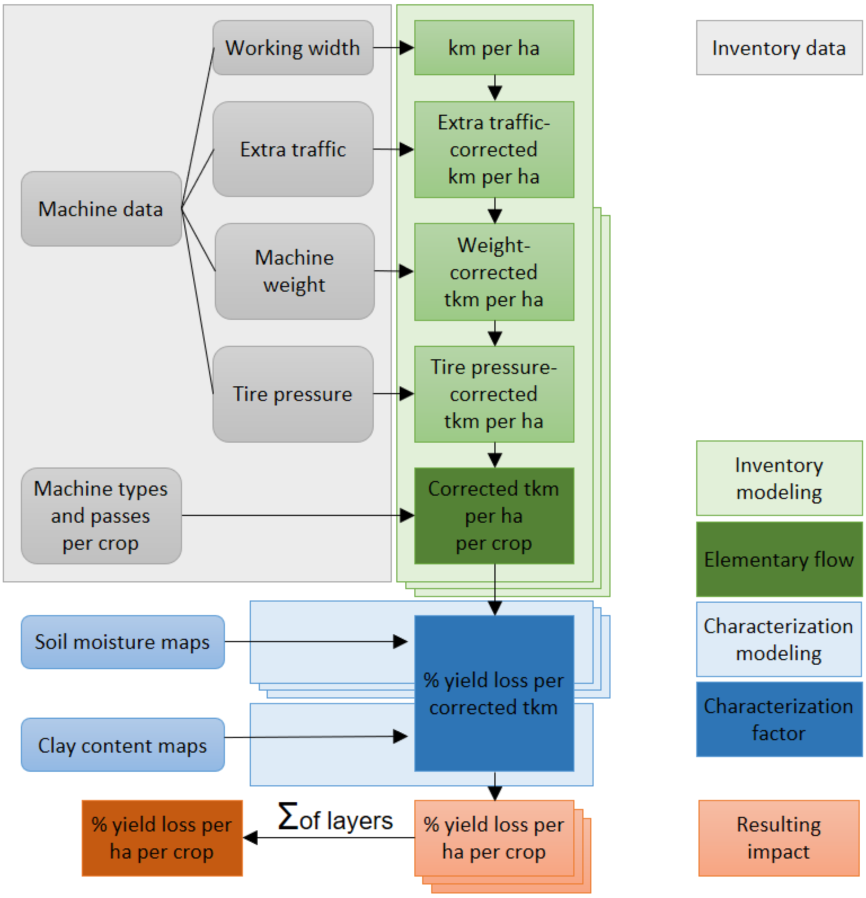

Figure 2: Modeling approach for calculation of elementary flows and characterization factors for three soil layers; rounded boxes represent the model input, layered rectangles represent the three soil layers for which separate calculations are made.

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 techno-sphere 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 (techno-sphere) 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 (Figure 2). 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. 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 Håkansson, 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). The model assumes 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 Håkansson, 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 (Equation 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.

$$\varnothing\ annual\ yield\ loss_{100y} = \frac{\%\ yield\ loss_{top\ soil}}{100y} + \frac{\%\ yield\ loss_{mid\ soil}}{100y} + \%\ yield\ loss_{bottom\ soil}/y \qquad \text{(Eq. 1)}$$

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 becomes linear. An example is provided in Figure 3.

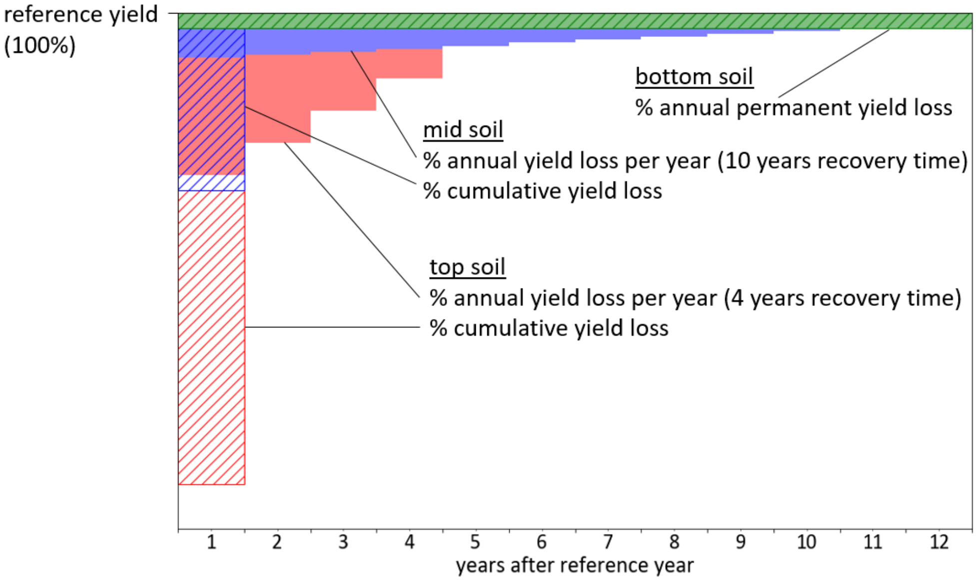

Figure 3: Dynamic impact modeling with linear recovery, in case of the top soil layer within 4 years, in case of the mid soil layer within 10 years; areas represent yield losses in % of yield in the reference year; hatched: model output, filled: model output assigned to different years with linear recovery, red: top soil layer, blue: mid soil layer, green: bottom soil layer.

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 Figure 1, 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, 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 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 Equation 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.

$$SMCV = soil\ stress\ coefficient \times 4 + 1 \quad \text{(Eq. 2)}$$

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 Equation 3, which simply computes the area weighted average of the SMCV and the irrigation value (which is 3).

$$SMCV_{irrigated} = \frac{area_{irrigated}}{area_{total}} \times SMCV + \frac{area_{not\ irrigated}}{area_{total}} \times 3 \quad \text{(Eq. 3)}$$

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 Håkansson, 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.

3. Results and Discussion

3.1. LCI Elementary Flow

Corrected tonne-kilometers per ha (as a proxy for the pressure on soil), which subsequently translates into compaction damage, is on average 16% higher for organic than for integrated crop farming. This is calculated for 24 pairs of crops in organic and integrated production according to Equation 4.

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

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. This is visible in Figure 4, which also shows that differences between the crops are bigger than between the crops produced in different mechanized production systems. This is partly due to the number of passes, but primarily due to the differing specific weights and working widths of the different kinds of machines used. 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 the latter is the number of passes in the fields. The corrected tkm per ha for 81 crops are presented for the three soil layers in a table in Appendix E.

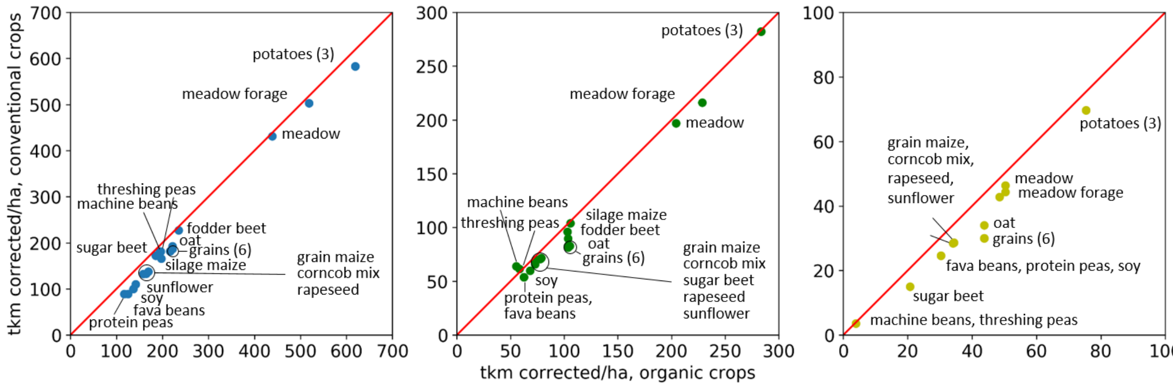

Figure 4: Comparison of pressure on soil for 24 organic (x-axis) and integrated (y-axis) crops for the three soil layers (left: top soil layer, middle: mid soil layer, right: bottom soil layer) (the unit is corrected tkm per ha, which is proportional to the impact for each soil layer at a given site). The line of equality is depicted in red and the number in brackets are the amount of crops and production methods for overlaying dots.

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, Figure 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).

The characterization factor presented implies a long-term use of the land assessed as agricultural land. However, also if the land would be 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 Figure 3).

3.3. Life Cycle Impact

The impacts of compaction are illustrated with potato and wheat production in cropping systems in Figure 5. 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. 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 costly harvesting procedure.

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, Figure 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, Figure 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, Figure A3, the global coverage of Figure 5 has the advantage that future sites of crop growth can also be taken into account to find out where it may be reasonable to expand crop-growing areas. Insights about potential compaction impacts are also useful when a transition from manually managed small-scale farming system (without significant compaction impacts) to more intensified, mechanized farming is planned. Finally, the presented analysis show which crops are suitable to minimize compaction impacts for a certain location.

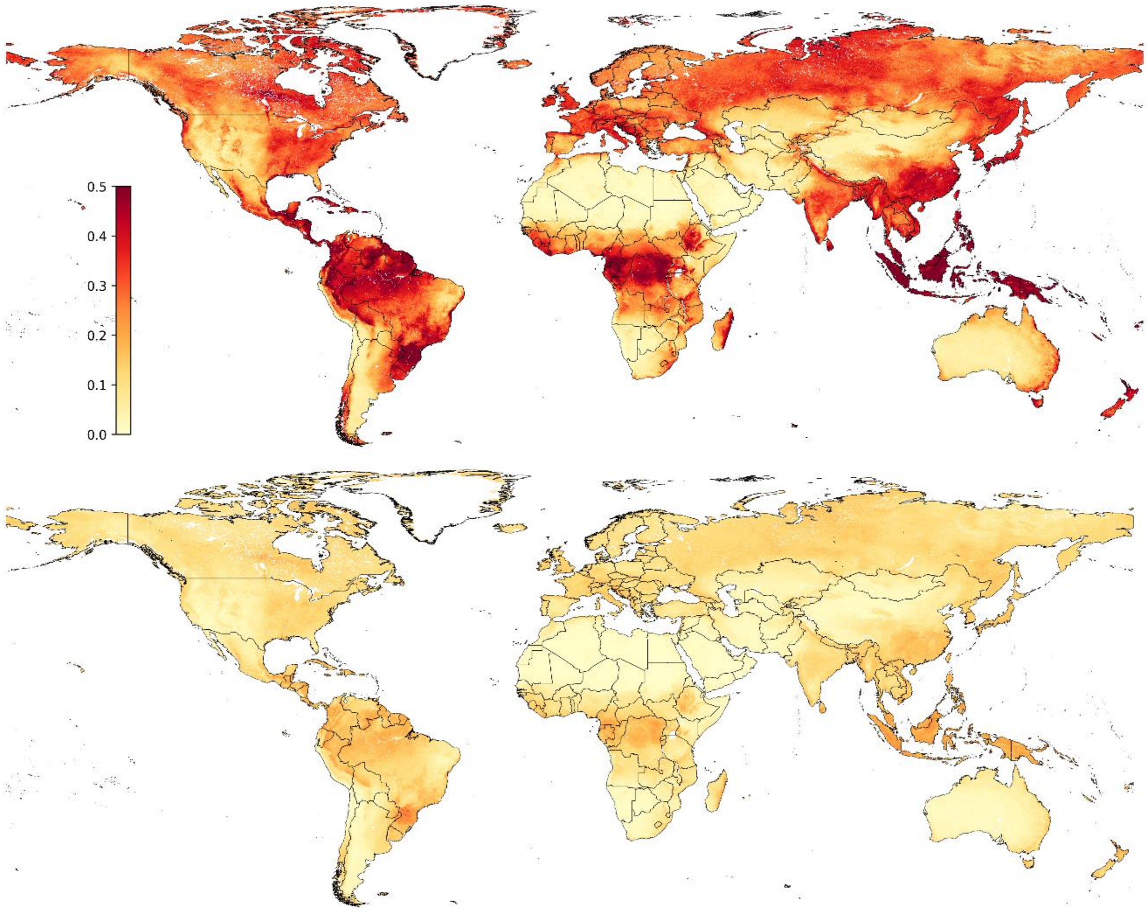

Figure 5: Comparison of impacts (average annual yield loss in % over 100 years) for potato (integrated, intensive) (upper part) and winter wheat (integrated, intensive) (lower part).

Yield losses due to soil compaction are relatively small, and are often not recognized because they are compensated through fertilization or different cultivation practices. Moreover, they underlie year-to-year variations. There are different strategies either to prevent yield loss (and other environmental effects) through soil compaction or to stimulate recovery in the top and mid soil layers through changed management strategies. Preventative management strategies are e.g. low soil moisture during field work, 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 (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., 2007b).

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 Håkansson, 2014). The results of recovering by subsoiling (tillage in deep soil layers) are moderate (Batey, 2009a).

4. Conclusion

Agricultural soils are under increasing pressure to produce more food, fuel, fodder and fabrics. Cultivation practices that do not follow good agricultural practices harm soils and their quality. As different soil degradation processes are on the rise, the production potential of soils decreases as a consequence. Nearly 99 % of the food production (in calories) for human consumption is from land-based production (Jones et al., 2012) and in addition soils fulfill a variety of other ecosystem services (Jónsson et al., 2017). This study offers a new method for the LCA practitioners to include impact assessment of soil compaction into life cycle assessment of agricultural products. It makes it possible to calculate potential compaction impacts of crop rotation scenarios and expansion of crop growing to new agricultural fields. This can be interesting in combination with climate change scenarios.

The comparison of the elementary flows of 24 pairs of organic and conventional crops revealed that the differences in impacts of production systems are smaller than the differences in impacts of different crops. Thus, to avoid compaction impacts, it is rather suggested to choose carefully the growing crop than to change from one production method to another.

The structures of the soils vary widely. In this study, it was possible to quantify the global characterization factors for the impact of soil compaction based on spatially highly resolved soil clay data (250 m, aggregated to 1 km) and soil moisture data in a resolution of 1 km. 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. It is reasonable to assume that the soil compaction impacts are being compensated for by heavier use of agricultural means of production, leading to further degradation until the land has to be abandoned.

5. Limitations and Further Development

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 (ETH et al., 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 Python™ code provided on Github (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 Håkansson, 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 Håkansson, 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 modelling 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 suitable for annual crops grown in moldboard ploughing crop systems, which represent approximately 90% of global agriculture. This is derived from the estimations of area under conservation tillage (7.4-11%), with the tendency to rise (Derpsch et al., 2010; Kassam et al., 2014; Lal, 2013). It restricts the overall usability, because it excludes, for example, modeling the impact of permanent crops and the production of crops from conservation tillage systems. The model should be extendable for perennial crops, as already demonstrated by the model developed by Braunack et al. (2006). In addition, an extension for conservation tillage systems would complete the possibilities for analysis, 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 the treading of grazing animals (Drewry et al., 2008), in forest harvesting, in recreation land use, and construction sites (Batey, 2009b). 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 in particular, 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, Figure 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.

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