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# Assessing the environmental impacts of soil compaction in Life Cycle Assessment

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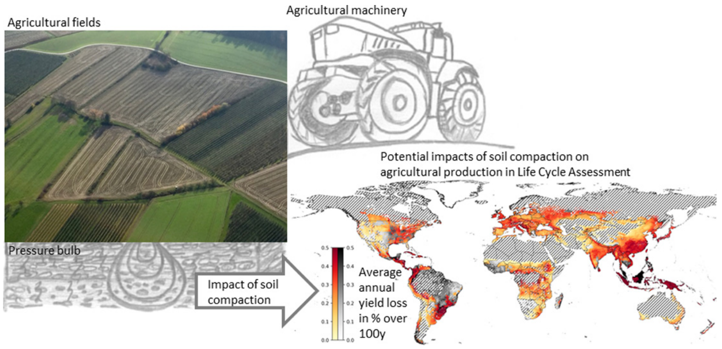
## HIGHLIGHTS

- 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.

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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