Soil research challenges in response to emerging agricultural soil management practices

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Abstract

Agricultural management is a key force affecting soil processes and soil functions. Triggered by rapid structural and technological developments new management practices emerge. Their impact on soil processes and soil functions is largely unknown. This impedes the assessment of the potential of such emerging practices for sustainable intensification, a paradigm coined to address the growing demand for food and non-food products. In terms of soil management, sustainable intensification means that soil productivity is increased while at the same time other soil functions and services, such as carbon storage and habitat for organisms, are maintained or even improved. In this paper we provide an overview of research challenges to better understand how emerging soil management practices affect soil processes and soil functions.

We distinguish four categories of future soil management (spatial arrangements of cropping systems, crops and rotations, mechanical pressures, and inputs into the soil). We identify key research needs for each of them, such as research on nutrient efficiency in agroforestry versus conventional cropping systems, soil-rhizosphere microbiome research to understand the interacting roles of crops and rotations, the effects of soil compaction on soil–plant–atmosphere interactions, and the ecotoxicity of plastics and pharmaceuticals brought into the soil. We set an interdisciplinary, systemic approach to soil science and include cross-cutting research activities related to process modelling, data management, stakeholder interaction, sustainability assessment and governance. This is a first overview of research needs around emerging agricultural management practices from a soil science perspective. It intends to facilitate interdisciplinary cooperation with agronomic and other researchers about sustainable agricultural production.

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1. Introduction

Bioeconomy strategies worldwide strive to substitute fossil resources with bio-based resources (Fund et al. 2015). Reinforced by a projected increase in demand for food and resource intensive diets (Alexander et al. 2015; Godfray and Robinson 2015; Kastner et al. 2012; Foresight 2011), this implies higher demand for biomass production from agricultural soils. However, fulfilling this demand sustainably requires a soil management that increases the production function of soils while it maintains or even improves other soil functions and services. These soil functions are the production of biomass, storing and filtering of water, storing and recycling of nutrients, habitat for organisms and carbon storage (Vogel et al. 2018). This endeavor can be seen in the broader context of the concepts of 'sustainable intensification' (Garnett et al. 2013) and 'ecological intensification' (Tittonell 2014) which initiated the challenge for agricultural management to increase production while minimizing resource use and intensifying ecological interactions in the soil–plant continuum. These ambitious concepts provoke numerous scientific challenges, including the understanding of the impact of soil management on soil processes and soil functions.

Soil science has created profound knowledge on soil properties and processes relevant for soil management and crop growth. Yet, huge knowledge gaps remain regarding the interaction between soil management practices and soil process responses (e.g. Poesen 2018, Key et al. 2016).

To address soil management questions from a soil science perspective, we need to better understand how current and especially future agricultural practices impact soil processes and functions. Besides the increasing demand from production on agricultural soils, other factors drive changes in agricultural soil management. These are socio-economic drivers such as policies, biophysical drivers such as climate change and technological drivers such as advancement in robotics. For instance we may see more lignocellulosic crops grown in agricultural systems inter alia due to demand from the bioeconomy. Changed crop varieties may occur inter alia due to changing environmental factors and new breeding techniques. Technological developments may drive changes in field traffic. And more contaminants from organic fertilizers are possible due to resource efficiency and circular economy strategies (Techen and Helming 2017).

An interdisciplinary team of researchers around the soil system is therefore required to understand research challenges stemming from emerging agricultural practices and to improve soil process understanding, synthesize the scientific knowledge into modelling and assessment and to provide evidence about opportunities and threats of different soil management practices so that stakeholders can make informed decisions on how to manage soils or into what directions to govern the management of soils.

In this paper, an interdisciplinary group of researchers being organized in the German research program "Soil as a sustainable resource for the bioeconomy –BonaRes" (www.bonares.de) jointly formulated key research challenges addressing the interplay between emerging agricultural management practices and soil processes. We have structured the identified research challenges along four categories of soil management, namely spatial arrangement of cropping systems, crop choices and crop rotations, mechanical pressures and inputs into the soil. A foresight on potential developments, including technological innovations, in these categories for the case of German agriculture was provided by Techen and Helming (2017). By formulating research challenges along the soil management categories we follow a systemic approach integrating across biological, physical and chemical aspects of soil sciences. This is to ensure connectivity to agronomic sciences and to support a better understanding of whether and how the sustainable intensification concept can indeed be operationalized. The spatial focus was laid on countries with temperate climate, high technological development level and low yield gaps, for which Germany is an example. The temporal focus was laid on the next five to ten years. This is longer than the ordinary research project lifetime but close enough to address perceived signals about emerging agricultural soil management practices. It still allows innovation to occur. It is also a time horizon of relevance for stakeholders.

Research challenges outlined in this article are meant to support interdisciplinary research towards better understanding opportunities for sustainable intensification and the integration of agricultural production with the other soil functions. Such understanding is relevant for agricultural researchers, modelers, soil management choices of farmers, politicians and other stakeholders.

2. Methods

Research challenges from a soil system perspective were identified by an interdisciplinary expert group, i.e. the authors, on the basis of state-of-the-art knowledge on the interaction between soil management, soil processes and emerging soil functions.

2.1 Composition of the expert group

The idea for this paper was motivated by the German research program "BonaRes – soil as a sustainable resource for the bioeconomy" (www.bonares.de). The program is funded by the Federal Ministry of Education and Research (BMBF) in the framework of the bioeconomy strategy of the German government to support the conservation and improvement of soil quality under increasing pressure from agricultural production to implement the bioeconomy strategy.

The expert group started out with the leading researchers (principle investigators) of the 10 interdisciplinary collaborative research projects of the BonaRes program plus the BonaRes Centre. The group then invited other team members to contribute with specific expertise on soil research challenges. Every author could comment on the full draft and the draft was revised until all authors agreed. The author group represents specific expertise in the field of agronomy, soil chemistry, soil biology, soil physics and soil mechanics. For the cross-cutting perspectives the group includes expertise on soil modelling, agronomy, sustainability assessment and agricultural as well institutional economy.

2.2 Structural Framework

The results of a foresight study about emerging soil management practices in Germany were used as the structural framework (Techen and Helming, 2017). The foresight study analysed drivers and trends of agricultural soil management in Germany in four management categories: spatial arrangements of cropping systems, crops and rotations, mechanical pressures on soil and inputs into the soil. The analysis was done by means of a literature review and was further substantiated by 19 interviews with 22 experts from soil science and related sciences (agriculture, climate change, modelling, agricultural technologies), from authorities (policy, administration) and agricultural practice (Techen and Helming 2018).

The structural framework (Figure 1) reflects potential changes within the next 20 years. Qualitative changes of soil management practices, such as the integration of new crops in crop rotations, mainly present opportunities for soil functions if the soil processes and impacts are well understood and if the practices are further developed and implemented according to this knowledge. The foresight study also anticipated quantitative changes (more/less of the same input factors) as part of an expected moderate intensification of agricultural production. But in this paper we focus exclusively on the analysis of qualitative changes, because they are anticipated to have larger implications for soil processes and changes of soil functions than purely quantitative changes of soil management. Research needs are outlined for the management categories of Figure 1, namely spatial arrangements of cropping systems such as agroforestry, crops and rotations such as new crop varieties, mechanical pressure such as changed weight and contact stresses, and inputs into the soil such as recycled nutrients products.

Complementary to research needs on soil processes as influenced by management and their impact on soil functions, research is also needed to upscale and generalize empirical observations and to synthesize generated knowledge into a basis for decision support. This involves data management to support research, and allow for data reuse such as in meta-studies. It involves the development of simulation models for a comparative assessment of alternative soil management options. Modelling is also a means for upscaling of localized knowledge to larger areas provided that the effects of space specific conditions are known. It also involves the assessment of soil management practices in regards to costs and resource use efficiency, social acceptance, risk for human health and impact on ecosystem services. Such research requires good methods of stakeholder involvement and user interaction to assure the practical usefulness of research results.

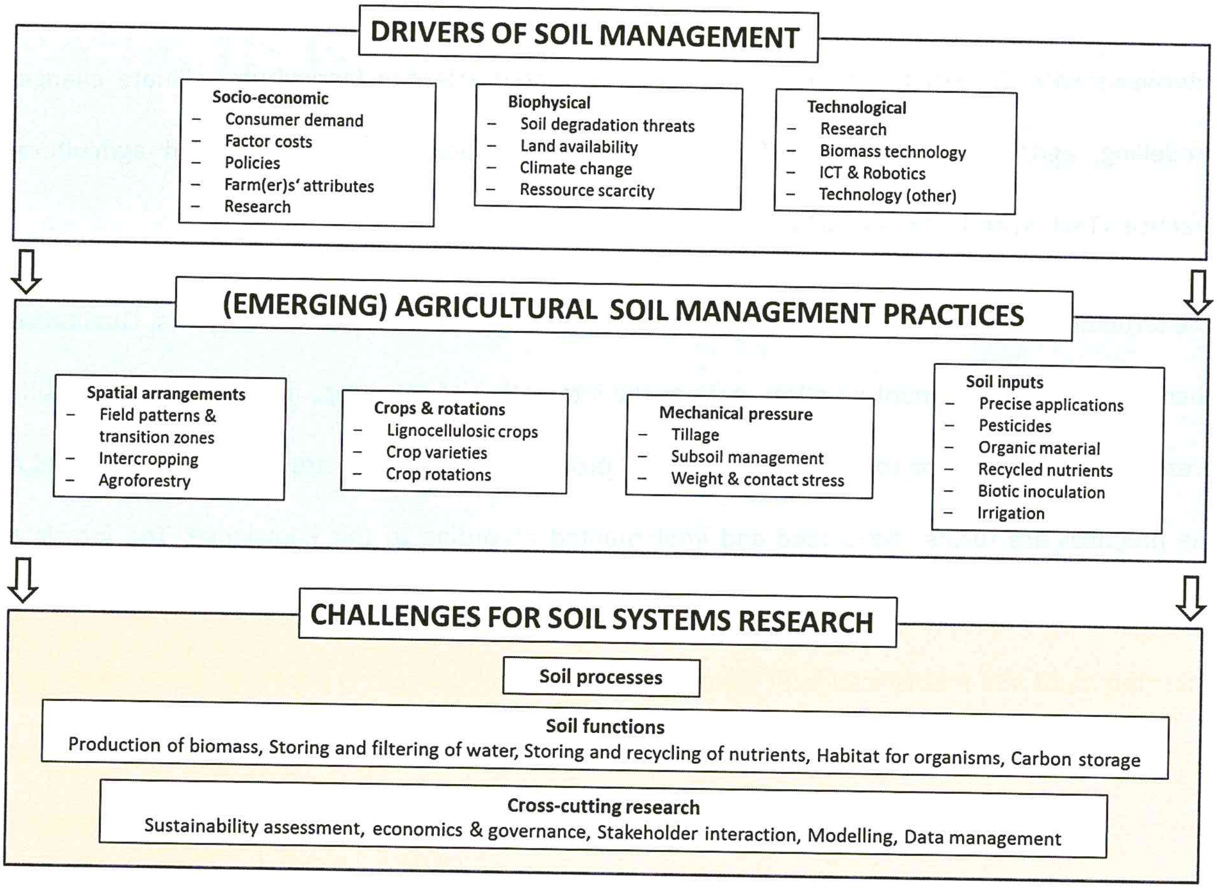

Figure 1: Structural framework for the identification of soil research challenges: socio-economic, biophysical and technological drivers (top) affect soil management in four categories of soil management (middle). These in turn affect soil processes and soil functions (bottom), for which research challenges are formulated. Purely quantitative changes of soil management (intensity) were not considered in the analysis. (Adapted from Techen and Helming 2017)

2.3 Methods for synthesis

We have formulated key research challenges from the research challenges identified in chapters 3 and 4. The respective experts among the authors of chapter 3 have estimated how strongly the results of the proposed research topics could influence soil functions, i.e. how relevant they are or may be for soil functions (Figure 3). Additionally Figure 4 presents the same key research challenges and their estimated potential influence on soil threats. They used a scale of 0 to 3. The assessment is shown in a graphical style to underline that the assessment is qualitative and there exists a connectivity among the soil functions and among the threats. The cross-cutting research challenges (Figure 5) were not assessed in terms of soil functions and soil threats since they are by default relevant for the whole spectrum.

3. Soil research challenges in response to agricultural soil management practices

In the following chapters 3.1 to 3.4, soil research challenges are presented along the emerging and changing agricultural soil management practices (Figure 1) that raise soil research questions, while cross-cutting research challenges are presented in chapter 4.

3.1 Spatial arrangements of cropping systems

Spatial arrangements of cropping systems are defined by the spatial extent and distribution of fields and crops as well as the quality of field transition zones, e.g., between different crops, fields or land use types. Field transition zones affect soil erosion (Van Oost et al. 2000), agricultural biodiversity (Heißenhuber et al. 2014), and potentially biological pest control (Médiène et al. 2011; Haenke et al. 2014), the latter affecting the need for pesticide application. Currently the trend towards larger fields and eliminating landscape elements is still ongoing in Germany triggered by large machinery sizes and the need for time efficient management activities. But in the coming 15 to 20 years this trend may reverse and it is well possible that farming machinery will become smaller (Techen and Helming 2018). This does not necessarily result in smaller field structures but it would ease the implementation, for instance, of policy measures to support smaller structures. Research shows increasingly that agroforestry and intercropping, as cropping systems with smaller scaled patterns and more transition zones, can have multiple benefits, also in temperate regions (Pelzer et al. 2014;

Yu et al. 2015; Torralba et al. 2016; Smith et al. 2013; Gou et al. 2016). Both agroforestry and intercropping are systems where two or more crops are grown simultaneously in the same field (Vandermeer 1989).

In the case of agroforestry, at least one of the system components consists of trees. Research may eventually drive their adoption, along with improving agricultural machines if they become smaller and allow for more spatial differentiation. Also the technological improvements in the use of lignocellulosic feedstocks for energy and industry could support a trend towards agroforestry by raising demand for woody crops and offering long-term contracts.

In general, growing trees with crops or two functionally different crops together will be beneficial when the tree component or the second crop will acquire resources (water, light or nutrients) complementary to the other crop, but will not be beneficial if both components are competing for the same resources (Cannell et al. 1996). Agroforestry systems are hypothesized to have a more efficient use of soil nutrients because tree roots can act as 'safety net' for leached nutrients (Lehmann et al. 1998), can take up nutrients from deep soil layers beyond the shallow-rooted crops (Dechert et al. 2005), and potentially utilize nutrients at times when crop demand is low. At present, there is however very limited research on these mechanisms in temperate agroforestry. One of the main challenges for large-scale implementation of agroforestry systems in Europe is that systems should be compatible with modern mechanized agriculture. In short rotation alley cropping systems, strips of fast growing trees are planted alternately with strips of annual crops or grasses (Quinkenstein et al. 2008). Such alley cropping systems are compatible with the use of modern agricultural machines, which is not always the case with other agroforestry systems. Since the trees in these alley cropping systems are managed as short rotation coppice for bioenergy production, potential competition for resources by the tree strips are controlled every few years when the aboveground biomass are cut. In this section, we mainly focus on short rotation alley cropping systems, but many of the arguments in favor of such systems are also valid for other agroforestry systems and partially for landscape elements such as hedge rows and wind breaks.

One of the main reasons why agroforestry is regarded as better than monoculture in improving ecological functions is because of the functional services of its tree component. Trees have positive effects on soil properties. In tropical and subtropical agroforestry systems, it has been shown that nutrient cycling under trees is relatively closed in contrast to annual crops (Dechert et al. 2005); that trees increase soil organic matter levels (Oelbermann et al. 2004), improve aggregate stability, and stimulate denitrification, resulting in reduced nitrate leaching (Ferrarini et al. 2017). Trees have often been used to reduce wind erosion in so-called 'windbreaks' (e.g. Brandle et al., 2004) and in areas affected by wind erosion, the integration of trees may provide short rotation alley cropping systems with a distinct advantage compared to monocultures (Quinkenstein et al., 2008). Although there are case studies showing that integration of tree alleys reduces wind speeds (e.g. Böhm et al, 2014), there is surprisingly little systematic research on the effectiveness of alley cropping systems to reduce wind erosion. The use of simulation models to assess how tree alley establishment and management can optimize reduction of wind erosion therefore appears to be a promising line of future research.

Trees also have positive effects on soil structure, resistance to erosion, cation exchange capacity, and storage of nutrients in soil organic matter (Dechert et al. 2004). The use of tree fallows to restore organic matter stocks during shifting cultivation illustrates the capacity of trees to restore soil carbon and nutrient stocks (Powers et al. 2011). This has also been shown by higher soil carbon levels in tree alleys compared to adjacent crops (reviewed by Tsonkova et al., 2012). These positive effects of trees are related to the permanent root systems and the absence of cultivation and fertilization.

When trees are grown simultaneously with annual crops, the whole agroforestry system can take advantage of the positive functional services of trees. Temperate agroforestry systems can thus have improved nutrient cycling compared to conventional agriculture. However, under which (soil) conditions this also leads to better nutrient response efficiencies and higher efficiencies with which nutrients are retained in agroforestry systems is an important research gap. Temperate agroforestry systems can also utilize water sources beyond the rooting zone of annual crops and outside the crop's growing season. However, under which soil conditions agroforestry systems can influence the overall water consumption at the field scale through reducing wind speed and increasing infiltration rate is still unclear (Herbst et al. 2007) and more research, in which the water use of whole agroforestry and conventional agriculture systems are systematically compared, is needed.

Agroforestry also has important effects on the microclimate through changes in wind speed, air humidity and provision of shade. Such microclimatic effects can have positive or negative effects on crop growth (Kanzler et al., 2018; Cleugh, 1998) but will also affect e.g. pathogenic fungi. There are only few case studies reporting such studies, and we were not able to find any focusing on pathogenic fungi or soil-borne diseases in temperate climate alley cropping systems, making this an important focus for future research.

In addition to a better surface cover, permanent root systems are also the main reason why integration of tree alley can significantly reduce soil water erosion. For example, tree alleys have higher water infiltration rates than adjacent crops, significantly reducing risk of runoff (Anderson et al., 2009). An optimal placement of tree alleys in a landscape (e.g. along contour lines, in so-called thalwegs, or as riparian buffers) may also significantly reduce sediment loss from agricultural fields (e.g. Palma et al., 2007), prevent gully development in concentration flow-lines (Slattery et al., 1994, or promote retention of suspended sediment particles (Christen & Dalgaard, 2013). Many studies on soil water erosion are still using the revised universal soil loss equation (RUSLE) without validation (e.g. Palma et al. 2007) and there is a clear need to evaluate the effectiveness of agroforestry systems in reducing soil water erosion at the landscape scale, using dynamic modelling approaches in combination with validation (e.g. Schoorl and Veldkamp, 2001). Soil erosion, transport and sedimentation strongly affect landscape-scale carbon budgets. At the eroding hillslopes, there is increased mineralization and a dynamic replacement of eroded C while at the foot slopes, significant amounts of soil organic carbon are buried in the subsoil, leading to slower mineralization rates (Doeterl et al, 2016). The net effect of these processes is often substantial sequestration of carbon at the landscape scale (e.g. Quine and van Oost, 2007). Since establishment of agroforestry systems will stimulate retention of eroded particles within the same field, we expect that this process will add to the carbon sequestration capacity of agroforestry systems. However, to our knowledge there has not been any research into quantifying how agroforestry affects landscape scale carbon budgets through erosion and sedimentation.

Figure 2: Wheat harvest in a short coppice alley cropping agroforestry system (©Marcus Schmidt).

In intercropping systems, typically crops alternate in strips, with strip width ranging from several plant rows to several meters, and this is also called 'strip-intercropping'. Relay cropping refers to intercropping systems in which the second crop is planted when the first is maturing (Federer, 1993). The central idea of strip-intercropping is that resources (water, light and nutrients) are converted more efficiently into yields than in monocultures. Furthermore, risks of crop failure may be lower and yield stability higher (Raseduzzaman & Jensen, 2017). Positive effects of legume-cereal intercropping systems are mainly due to N input from symbiotic N fixation (Munz et al. 2014). Cereal-cereal intercropping system (e.g. C3-wheat and C4-maize) also show considerable increase in the land equivalent ratio (LER: the ratio of the area under monoculture cropping to the area under intercropping that is needed to give equal yield under the same management level), which appear to take advantage of temporal niche differentiation (Yu et al. 2015). Although literature shows that intercropping can have advantages on yield stability and productivity (Raseduzzaman & Jensen, 2017), important research gaps need to be filled. In general there is a lack of systematic comparisons of intercropping systems with monocultures in Germany and other regions with similar agronomic and climatic conditions, and since successful strip-intercropping systems need a site-specific choice of compatible crops, suitable cultivars (e.g. shade-tolerant cultivars) and adapted management (e.g. width of crop strips and timing of sowing and fertilizer application) this is a major research gap. Field experiments on intercropping should have a focus on competition for resources (water, nutrients and light) since this ultimately decides whether intercropping has advantages over monocultures. For example, in a wheat-maize system, wheat in the border rows started with less competition than wheat in the inner rows; however, competition in border rows intensified during the crop development, negatively affecting maize biomass (Gou et al. 2016). Another major challenge will be to mechanize strip-intercropping systems; otherwise, labor costs will make these systems financially less competitive even if they may have ecological and agronomic advantages over monocultures.

3.2 Crops and rotations

The choice of crops and crop rotations affect soil functions because crops differ, for example, in their root systems, their interacting biological soil processes, the potential of the rhizobiome and roots to mobilize and take up nutrients, the degree and duration to which crops cover the soil and the residues they leave after harvest. All of this is paramount for soil organic matter turnover, soil stability and erosion, and soil biota, which are all relevant for soil functions.

Farmers are expected to adapt to climate change-induced developments such as different rainfall patterns and longer growing seasons in the long term (past 2040) and changed weed systems by using different plant varieties. In addition changing consumers demands and/or policies affect economic conditions and lead to changes of the relative shares of crops in the rotations (Techen and Helming 2017). For example, if more lignocellulosic feedstocks should be demanded in the future, this could drive the integration of lignocellulosic crops in pure plantations with trees (short rotation coppice) or perennial plants such as *Miscanthus*. This may potentially improve all soil functions, for example by increasing soil organic matter content and improving soil stability. Agroforestry is also an example of this integration but due to its specific spatial arrangements it is addressed in section 3.1.

The concept of diversity in cropping systems is traditional and successful since millennia, but industrialized farming practices have led to simplified cropping systems. As a consequence, pests and diseases have to be kept under control by the application of agrochemicals, and soil fertility has to be maintained by excessive fertilizer use, both yielding dramatic side effects to a plethora of ecosystem services. Therefore, overcoming the loss of biodiversity in agroecosystems is key to maintaining soil fertility and assuring food security (Tscharntke et al., 2012), and may need more support from researchers quantifying long-term effects on soil functions and costs and benefits of diversified crop rotations for farmers and society.

So far, breeders' efforts were mostly focused on improving aboveground characteristics, whereas phenotyping of root traits is much more difficult let alone root growth in native soils or root–soil interactions. Thus they have received much less attention in the past. It is known, that plant root exudates shape the rhizosphere microbiome and thereby also soil structure in a genotype dependent and inheritable way. Thus, future breeding activities could also address selecting varieties that via their root exudation support the growth of the crop itself, following crops and thus soil habitat functions. Moreover, genetic diversity within crops but also in crop rotations and catch crop selection will have an impact on rhizosphere and soil (micro)biomes and their functions (Peres-Jaramillo et al. 2016). However, this will need big data approaches and most likely several years before being realized in the first crops. Classical breeding supported by marker-assisted selection and biotechnology, but also modern tools like gene editing via CRIPSR Cas9 (Clustered Regularly-Interspaced Short Palindromic Repeats) technologies, which enable directed genetic manipulations (Arora and Narula 2017), will help breeders to implement some of the traits mentioned. In order to support breeding in this regard, fundamental soil and plant research addressing the genetic base of traits such as root architecture, rooting depth, water and nutrient use efficiency, root exudate composition or rhizosphere soil structuring are needed (Lammerts van Bueren et al. 2014).

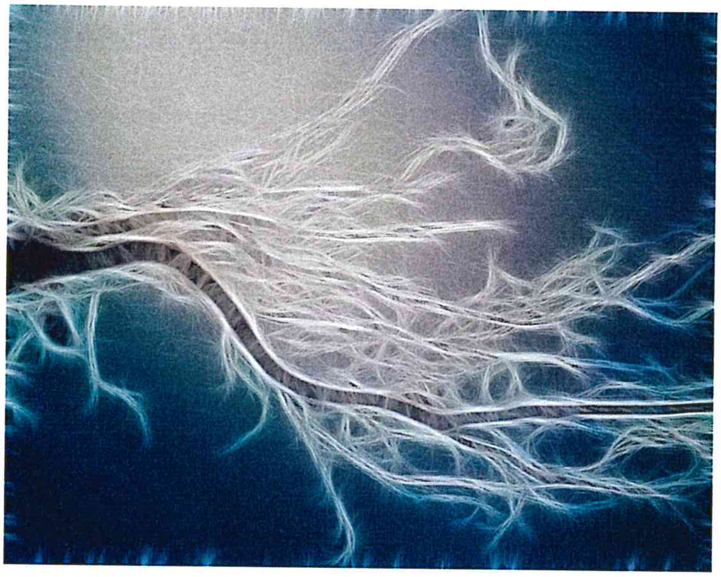

Figure X1: Roots (kein Bildnachweis nötig) (künstlerisch wertvoll aber kein Boden zu sehen)

Apart from breeding, the general idea of beneficial effects of biodiversity in agroecosystems is based on three core columns: functional redundancy, functional niching, and the fostering of diversity-driven ecosystem services. Although some of the services are not directly related to crop yield, they generally enhance ecosystem functioning and resilience (Frison et al., 2011).

There are several options to increase the spatial and temporal diversity in agricultural systems: intercropping/companion planting (see 3.1), intraspecific crop diversification (within-crop diversity), crop rotation, catch cropping and symbiotic chain management. Intensification of cropping cycles by integrating agrobiodiversity and reduction of bare fallow periods are paramount for the optimization of nutrient cycling, erosion control, and land use efficiency. Crop rotation has been applied for thousands of years, and it is commonly accepted that crop rotation increases yield and profit and allows for continuous production. One way to improve diversity in crop rotation is the inclusion of catch crops in the system. The advantages of catch cropping on soil functions have been widely investigated and range from protection from soil erosion and nutrient leaching via improvement of nutrient cycling (Thorup-Kristensen et al., 2003) to C sequestration and climate change mitigation strategies (Poeplau and Don, 2015). Catch crops have been shown to increase soil quality by improving biological, chemical and physical soil properties including: organic carbon content, cation exchange capacity, microbial biomass and diversity, aggregate stability, and water use efficiency (Dabney et al., 2001). Most of the studies, however, focused on the application of single catch crop species or blends of two species (Tribouillois et al., 2016). Highly diversified catch crops in blends of various species (5 to 20) with different rooting depth, trophic levels and symbiotic relationships emerged as a promising tool to further improve the advantages of catch cropping. However, studies on highly diversified catch crops are very scarce so far. Currently little is known how farming practices affect the diversity and functioning of complex soil microbial communities that are responsible for a range of soil functions such as storing and recycling nutrients into plant available forms. Key et al. (2016) assessed the impact of 27 management practices on soil health by a synopsis of soil literature that specifically test the effect of farming practices on soil fertility. They found that soil amendments, cover crops and use of crop rotation had the highest certainty and effectiveness scores related to beneficial effects on so il.

Management of functional redundancy and functional niching can as well (and ideally) be controlled by catch cropping. Although little emphasis was put on the management of symbiotic chains related to catch cropping so far, this factor seems especially rewarding. Mycorrhiza allows for several combinations between certain arbuscular mycorrhizal fungi (AMF) species and plants, thus the performance of a catch crop as well as of the cash crop itself is believed to have a certain plasticity due to potentially varying alliances and might thus change between years with different given environmental constraints. Since AMF are spore-forming, the genetical reservoir in soil can increase from rotation to rotation. Most of the functions mentioned above have been reported to be influenced by mycorrhiza in classical papers, but have not been evaluated for their interplay in catch cropping: nutrient niching (Anderson et al., 1984), pathogen control (Azcón-Aguilar and Barea, 1997), drought control (Ruiz-Lozano et al., 1995), or carbon sequestration (Treseder, 2004). As mycorrhizal fungi are bridging the gap between photosynthate production and the microbial community in the mycorrhizosphere (Jansa et al., 2013), functional redundancy and niching can be expected to be enhanced across all trophic strata in soil, but has still to be investigated.

Additionally, plants are colonized by complex microbial communities and their assembly depends on, among other factors, the microbial species that occur in the surrounding environment. The root-soil interface provides a hotspot for microbial activity with multiple niches for microbes, the root interior (endorhizosphere), rhizoplane and rhizosphere soil (Reinhold-Hurek et al., 2015), towards the inside gradually tending to lower diversity and a higher degree of specialization of the microbiome (Reinhold-Hurek et al., 2015). Differences in microbial community composition and diversity exist depending e.g. on development stage and plant genotype. The interplay of these microorganisms with the plant can have pronounced effects on plant traits (e.g., growth, health). In turn root/rhizosphere microbiota influence the soil microbiota. Studies of natural and agricultural systems have shown large effects of plant-soil feedback on plant growth (Marotte et al., 2017). But, the concepts and approaches used in these contrasting systems have mostly developed independently. Although microorganisms are an integral component of soils, their functions and activities received little attention in agricultural management strategies, yet. Despite the enormous progress in understanding the essential relationship between soil and plant microbiomes for soil functioning and plant traits (Reinhold-Hurek et al., 2015), information on variation depending especially on farming practices including use of crop rotation are still incomplete.

Here, we identified a knowledge gap, where research on the impact of diversified catch crop mixtures along with their symbionts on soil functions is highly demanded. Functional traits between species and their interaction with the soil-rhizosphere microbiome and their potential benefits for plant nutrition of the cash crops should be investigated. Catch crops have shown to reveal their full potential on crop yield improvements under low fertilizer treatments, in organic cropping systems, and under reduced soil management (Dorn et al., 2017). Future studies should, thus, focus on fertilizer reduction and on in situ improvement of soil fertility by crop rotation, catch crops and crop diversity. Reducing the input of fossil fuel driven energy in agroecosystems by supporting the indigenous soil food webs, fostering internal nutrient cycles and activating natural pest and disease management functions, while at the same time change from a chemical towards an ecological intensification of food production is the challenge of future research. Improvement of biodiversity should be one of the key tools on climate change mitigation and adaption strategies in agricultural systems.

3.3 Mechanical pressures on soil

Mechanical pressures on soil can damage soil structure, lead to compaction and erosion and disturb soil biota, all severely damaging soil functions, including the production function (Schjønning et al. 2015). Alongside the undesirable effects, for instance of soil compaction, on the soil functions, operational costs for remediation and alleviation measures, as well as environmental costs occur (Hamza & Anderson, 2005; Chamen et al., 2015; Keller et al., 2017).

Figure X2: Heavy machinery can cause compaction (kein Bildnachweis nötig)

High wheel loads of agricultural machinery and repeated wheel passages due to intense field traffic on cropland significantly increase the susceptibility of soil to soil deformation and compaction (Håkansson & Reeder, 1994; Hamza & Anderson, 2005; Nawaz et al., 2013). Recently, Schjønning et al. (2016b) supposed that a quarter of all European soils have been compacted. One reason for the high percentage of compacted areas is the strongly increased mass of agricultural machinery over the last decades (Schjønning et al., 2015b). Modern farm vehicles such as sugar beet harvesters or slurry spreaders can reach wheel loads exceeding 10 Mg. Assuming that the trend of increasing wheel loads will continue unless technological innovation or a paradigm change gain ground (Keller et al., 2017), a further expansion of soil compaction is expected.

Due to those problems, solutions to mitigate pressures from heavy machines, such as optimizing field traffic (Bochtis et al., 2014) and full automatic tire pressure regulation (Brunotte and Lorenz 2015), are being developed with good chances for implementation in the coming years. Already today, typical technological measures to mitigate soil compaction are reducing tire inflation pressure, increasing contact area of the tire, reducing wheel load (e.g. Chamen et al., 2015). In principle, these developments bear potential to reduce soil compaction. However, these soil-protecting effects are partly cancelled out if working widths and bunker capacities, and thus the total mass of the machines, are increased at the same time or when the machine is used more frequently under unfavourable soil conditions.

This makes the development of smaller machines relevant, even though the trade-offs between larger machines with fewer wheeled lanes and smaller machines with more wheeled lanes, are still unclear. Smaller and autonomous farming machinery, i.e. agricultural robots, are being developed with some chances of being implemented in the next 15 to 20 years, according to expert interviews (Techen and Helming 2018).

While tillage can also be used to mitigate compaction in the upper soil layer, reduced tillage has positive implications for soil processes and functions, such as storing and recycling of nutrients, storing and filtering water and habitat for organisms (Warkentin 2001). Reduced tillage is also an efficient measure to reduce soil erosion because the soil surface is covered with residue and soil sealing is avoided (Bradford and Young, 1994; Mhazo et al., 2016). A current trend towards reduced tillage would be counteracted by more frequent tillage and an increased share of tillage with the plow, at least in the short term, if major pesticides, such as glyphosate, were banned (Kehlenbeck et al. 2015). In contrast to compaction in the regularly tilled upper soil layer, subsoil compaction is hardly repairable because the intensity of regeneration processes decreases with increasing depth depending on soil and climate conditions (Håkansson et al. 2003). One option to overcome this problem is to apply mechanical loosening of the subsoil. However, this technique is energetically expensive and usually not long-lasting so that it does frequently not gain the required reimbursement of costs in routine agriculture practice (Schneider et al., 2017). Overcoming subsoil compaction by combined biological and technical options has thus become a novel research challenge.

Especially under moist soil conditions, the resisting forces of the soil are in imbalance with external forces imposed on soil through field traffic activity (Peth et al., 2006), resulting in soil compaction. While the contact area pressure mainly influences topsoil compaction, the subsoil compaction depends on the overall wheel load (e.g. Alakukku et al. 2003, Arvidsson & Keller, 2007; Lamandé & Schjønning, 2011). Additionally, the number of wheel passages affects the degree of soil compaction. While the first pass of a farm vehicle contributes to total soil compaction to the major part, repeated wheeling at the same or a higher wheel load increases the risk of subsoil compaction (e.g. Botta et al., 2009).

In addition to the mechanical load of the machine, the load-bearing capacity and thus the trafficability of the soil depends, besides the soil moisture, on soil structure, the organic matter content and the change in these properties within a soil profile, as well as on the cultivated crop. Depending on these parameters, the driving situation can change from solid, trafficable soil to plastically deformable soil, on which field traffic can damage the soil and its functions and, finally reduce yields. In general, the load-bearing capacity of soils decreases with increasing soil moisture and the susceptibility of soil to compaction increases.

Despite the understanding of main soil compaction causes, processes and consequences, there are many knowledge gaps and requirements in soil compaction research as listed below (without any ranking in importance):

Many studies focused on stress-propagation during wheeling and soil compaction effects on soil properties (e.g. Berisso et al., 2013, Arvidsson and Keller 2007, Schjønning et al. 2015a). Even though farmers are aware of the relevance of soil moisture and weather conditions, the knowledge about the quantitative effects of soil compaction and soil deformation on soil structure, soil structure dynamic and related soil physical, chemical and biological processes is limited (Vereecken et al., 2016) and needs further research. Further studies are needed to better understand the various relationships between soil compaction and its response in crop development (root, stem, leaf), crop yield and yield quality. While some studies show decreased yield in compacted areas (e.g. Radford et al., 2007), other studies found no significant effects (e.g. Schjønning et al., 2016a; Sivarajan et al., 2018). Long-term analyses of yield in compacted areas, however, are missing but are necessary to evaluate soil compaction.

Research often focusses on soil compaction, even though there are many environmental issues. What we need is a systemic view (Vogel et al., 2018, also Section 4) on soil and its interrelations with other environmental compartments. For instance, soil erosion and surface runoff depend on soil compaction as well (e.g. Alaoui et al., 2018). Simultaneously, the soil compaction risk is higher in deposition areas due to a lack of soil structure. Not only different disciplines but also sub-disciplines need to cooperate more closely to contribute to a better systemic understanding of the interrelated processes in agricultural landscapes.

Wheel load and contact area pressure is mostly assumed to be static (Vereecken et al., 2016). In practice, both are highly dynamic and change continuously e.g. during harvest (Duttmann et al., 2013). There is a need to consider the responses of soil due to dynamic load input, load transfer and deformation behavior under rolling wheels (e.g. Schjønning et al., 2015a) to get a more realistic view of soil compaction.

However, the use of large machines is not to be assessed as negative in general. By reducing wheeling intensity, a higher proportion of the field can remain unaffected by wheeling. However, the wheeled area by the larger (and possible heavier) machinery may result in a higher degree of soil compaction. An evaluation is necessary if the larger working width (including heavier machinery but less wheeled area) is better compared to lower working widths but possibly more wheeled area.

A key measure to prevent harmful soil compaction and to maintain the various soil functions is to optimize field traffic e.g. by regarding route optimization and material flow (e.g. Hameed et al., 2012; Bochtis et al., 2014; Edwards et al., 2017). As shown by Duttmann et al. (2013), field traffic during silage maize harvest can be irregular and confusing. An optimized coordination of all involved machineries will reduce unnecessary wheeling. Furthermore, a real-time adjustment of machine loads and machinery-induced stresses to soil mechanical strengths given exactly at the same time when the soil will be trafficked will reduce the soil compaction risk.

Depending on the spatially and temporally varying soil characteristics (e.g. soil moisture and moisture-related mechanical properties), meteorological conditions and field management practices the susceptibility of soils to compaction considerably changes throughout a year and from one day to the other. The intra-annual variation of soil moisture, soil mechanical strength and machinery-induced stress inputs are usually not considered in soil compaction assessments on the regional to the supra-regional scales. Lorenz et al. (2016) give examples how trafficability may change during the year. The consideration of dynamic changes in soil properties need further field analyses and integration in soil compaction modeling.

For subsoils, there is increasing evidence that its properties affect spatial distribution of, e.g., leaf area indices in the landscape (von Hebel et al., 2014). Also, improved yields are frequently observed immediately after subsoil loosening by, e.g., deep tillage, preferably in regions affected by drought (Schneider et al., 2017). Even if such positive effects can hardly be sustained for prolonged periods of time, likely because simple subsoil decompaction is not irreversible, the findings clearly show that subsoil compaction may impede plant growth whereas certain deep rooting crops can help mitigate subsoil compaction (see below).

Classical soil sampling and soil measurements are very helpful to analyze soil compaction effects but are time and labor consuming. To perform surveys, novel penetrometer devices are under development that simultaneously allow to measure soil texture via friction (Schmittmann and

Schulze-Lammers, 2018). Additionally, there is a range of geophysical tools available such as ground-penetration radar or electric resistance tomography that may provide indirect measures on soil water distribution and porosity (see, e.g., Vereecken et al., 2016).

At field scale soil compaction can exhibit a huge spatial variability. With site-specific treatment of soil compaction only parts of the fields need to be ploughed and considerable amount of fuel can be saved (Kichler et al., 2007). However, the mapping of within field variation of soil compaction is a formidable task which is not sufficiently solved up to date. Vertical cone penetrometers have been used for long in agriculture to detect soil compaction. They measure penetration resistance (soil strength) while they are inserted into the soil. The cone index is calculated from the penetration force per unit base area of the cone. Factors affecting the cone index include bulk density, soil moisture, soil type and soil structure (Ayers, Perumpal, 1982, Domsch et al., 2006). Efforts were made to design automated cone penetrometers with GPS registration for soil mapping which operate in a stop-and-go mode (Drummond, Christy, Lund, 2000, Domsch et al., 2006). However, due to high variability of penetration resistance and the requirement to probe within short distances mapping of a field with vertical penetrometers is uneconomic (Domsch et al. 2006). Consequently, systems for continuous mapping are favoured. There are three main approaches: a) horizontal penetrometers which measure the horizontal penetration resistance (Andrade-Sanchez, Upadhyaya, Jenkins, 2007), b) draft force sensors and vertical force sensors which are attached between the tractor and a tillage implement (Hemmat & Adamchuk, 2008, Tsiropoulos et al., 2015) and c) registration of fuel consumption of the tractor during tillage operation (Boon et al., 2005, Kichler et al., 2007). Hemmat & Adamchuk (2008) provide a thorough review of penetrometer system and draft force /vertical force sensors. Shamal, Alhwaimel, Mouazen (2015) describe an integrated system of three sensors for bulk density mapping. Measuring fuel consumption is an elegant approach which implements the "tractor as a sensor". However, as with the other approaches, translating fuel consumption into soil compaction and prescription maps is difficult. Up to now, none of the approaches for continuous mobile mechanical sensing were transferred into practice.

The use of newer imaging techniques as X-ray tomography (e.g. Naveed et al., 2016) are one way to describe the soil structure and assess soil functions in a more reliable way (Rabot et al., 2018). The use of remote sensing technologies may enable a faster and spatially broader collection of data. Therefore, research should focus on different remote sensing technologies (e.g. EMI, geo radar, unmanned aerial vehicle, satellites) and how these technologies may be used in soil compaction analyses at different spatial scales.

Some models are available to calculate the stress-distribution and stress propagation in the soil (e.g. Keller et al., 2007, Diserens & Battiato, 2013) and to estimate the potential soil compaction risk (e.g. Rücknagel et al., 2015). These are based on the principles of Bussinesq (1885), Fröhlich (1934) and Söhne (1953) and consider only soil pressure. They are often based on calculation formulas for the contact area and the pressure propagation within the soil. In contrast, Schjönning et al. (2008) provided a model (FRIDA) to calculate the stress distribution within the contact area. Existing soil pressure models regard the entire soil as a homogeneous, isotropic and non-layered medium. Since in reality the soil is divided into different layers, with different soil physical characteristics, such pressure calculations only provide idealized approximations. The translation into real conditions can lead to misinterpretations.

Most soil compaction modeling studies are available for 1D (e.g. Stettler et al., 2014), for 2D (e.g. D'Or & Destain, 2014) and for 2,5D (e.g., Keller et al. 2007; Schjønning et al. 2008, 2015) layer for different depths, but not real 3D connections. 3D modeling is rare (e.g. Duttmann et al., 2014) and 4D is not available.

Most soil compaction research is done in the laboratory (e.g. Canillas & Salokhe, 2002) or by single plots during wheeling experiments (e.g. Keller et al., 2014). The transferability of these results to field or regional scale is limited (e.g. van den Akker & Hoogland, 2011; Keller et al., 2017). As bulk density might not be homogeneously distributed in the landscape, effective parameters for soil compaction are needed to allow an upscaling of soil compaction effects from laboratory measurements to the field scale, with the need to provide also an upscaling to regional and landscape scale (Vereecken et al., 2016). The upscaling is necessary to e.g. understand where and to what extent soil compaction may occur and, in a next step, to prevent possible soil compaction. To achieve this aim, Vereecken et al., 2016 called for the development of a simplified semi-empirical soil compaction model for the ecosystem-scale. A modelling approach to predict the spatio-temporally varying patterns of soil compaction risk at regional scales has been described by Kuhwald et al. 2018.

Status surveys and Permanent Soil Observation Areas (BDF), which describe the actual soil structure condition and a possible endangerment of soil functions, could clarify the extent and distribution of soil compaction e.g. in Germany and Europe. Taking Germany as example, it shows that unfortunately such studies are only available in a few federal states or regions (e.g. Brandhuber 2005, Brunotte et al. 2008, Cramer et al. 2006, Eckert et al. 2006, Harrach et al. 2003, Isensee & Schwark 2006). Reviews can be found at Brunotte et al. (2008) or Lorenz (2008). An overview of works and surveys on the status of soil compaction in Europe is provided by Vorderbrügge & Brunotte (2011), Houskova und Montanarella (2008 a; b), Le Bas et al. (2006) and Schjönning et al. (2016). In future, there is a need of reliable information about the spatial distribution and extend of soil compaction. Therefore, coordinated long-term surveys about the status of soil compaction on arable land, grassland, fruit orchards, and in the forests are necessary.

Little work is done on the question, how compacted soil is able to recover or if it will remain as persistent compaction (e.g. Alakukku, 1996; Radford et al., 2007; Berisso et al., 2012; Besson et al., 2013). Processes as freezing/thawing, swelling/shrinking, root penetration or earthworm activity may contribute to recover compacted soil. The rate of recovery, soil structure evolution after compaction, long-term behavior after compaction considering physical, biological, chemical soil properties and yield responses, however, are unknown. Keller et al. (2017) claimed the need of long-term systematic field observations with adequate research infrastructure for monitoring to understand the mechanisms of soil structure recovery.

Mitigation of subsoil compaction requires high energy inputs, e.g. for deep tillage, and thus often not sustainable from an economic point of view. In addition, deep tillage includes the risk of diluting beneficial topsoil properties with subsoil material. Novel ideas thus aim at combining deep subsoiling with biological and improved technical measures. Particularly the use of deep-rooting pre-crops such as legumes or chicory forms biopores that facilitate subsoil access by reduced penetration resistance (McCallum et al., 2004; Perkons et al., 2014). Anecic earthworms lateron utilize these biopores for their own vertical movement into soil, therewith stabilize them with their faeces (Athmann et al., 2017), while providing at the same time surfaces with elevated nutrient supply and turnover (Barej et al., 2014; Han et al., 2017; Bauke et al., 2018). Future biological means might aim thus to include these effects directly into crop rotation, e.g., by the use of deep-rooting intercrops.

3.4 Inputs into the soil

On the one hand inputs into the soil, such as fertilizers and organic input, can improve soil functions. For example, manure delivers organic material and nutrients to the soil. On the other hand, inputs can harm soil functions, such as when pesticides disturb the soil biological system.

There are signals for several trends of changes in inputs into the soil, for which soil research is needed to clarify opportunities and threats and to contribute to the development of changed management options. These include changes in organic inputs and recycled nutrients, biotic inoculation, irrigation, and changes in the precision of fertilizer and pesticide application. Adding lignocellulosic crops to cropping systems and changes in crop rotations both also change organic matter in the soil, but are discussed in sections 3.1 and 3.2, respectively.

Soil organic matter plays a key role for soil quality by improving soil physicochemical and biological properties (Swift, 2001). However, around the world intensive agricultural practices associated with lack of or reduced organic matter inputs have significantly depleted soil organic carbon (SOC) stocks in many regions of the world (Lal, 2013). In many countries, easily accessible synthetic fertilizers combined with specialization of farms have resulted in a dramatic decrease in the use of farmyard manures (Maltas et al., 2018) and significant decreasing SOC stocks when no alternative management practices were taken (Fließbach et al. 2007). Stagnating inputs of crop residues (induced by stagnating yields of cereals and other crops) may have additionally contributed to SOC decreases in agricultural soils (Wiesmeier et al. 2015), although in many regions also legacy effects from former land conversion still contribute to current SOC losses (e.g., Steinmann et al., 2016; Sandermann et al., 2017). Additionally, increased use of crop residues for energetic and material uses is currently being discussed along with new biomass use technologies that are being developed (e.g. Weiser et al. 2014; Thrän et al. 2016). This would further decrease organic input into agricultural soils. However, farmers have long been aware of the important role of organic matter in soil fertility and there are signs that organic matter is gaining stronger awareness among different stakeholders in the context of soil biota and climate change (Techen and Helming 2017).

Regarding climate change mitigation, Smith et al. (2007) estimated that up to 90% of the total mitigation potential in the agricultural sector could be derived from SOC sequestration, with about 10% from reduction of non-CO2 greenhouse gases. This potential has been acknowledged in the '4 per 1000' initiative (https://www.4p1000.org/), which was proposed by France during the 21st Conference of the Parties (COP 21) of the UNFCCC in December 2015 in Paris. The final aims might not be reached, because, among others, pristine ecosystems may already store the maximum amount of SOC, and not all ecosystems are accessible to C sequestration management, particularly when sealed. Furthermore, a 4 per 1000 increase suggests a curve pattern that is far from reality because C sequestration rates, if not even showing a time lag, i.e., sigmoidal curve shape, at least follows a saturation pattern, with less potential C uptake close to C saturation (e.g., Preger et al., 2010). Yet, this initiative may foster research on how much and how fast C may be sequestered sustainably in soil, what is a current baseline for maximum C uptake, and which are potential target regions (Minasny et al., 2017; deVries et al., 2018; Duarte et al., 2018). This is of particular importance, as the carbon input by plants, particularly the belowground input in form of roots and rhizodeposition, is largely unknown (Kuzyakov & Domanski 2000; Pausch & Kuzyakov 2017). This emphasizes the need for precise quantification of above- and belowground carbon input by different crops/varieties in space and time to improve SOC management (see also Section 3.2).

In addition to direct carbon input by crops, application of organic soil amendments with high carbon (HCA) content, such as straw, sawdust and biochar, have received growing attention in the recent past as means for increasing SOC content and for improving the physical, biological and chemical functions of the soil. Long-term input of exogenous HCA has been shown to increase SOC content and thus carbon sequestration, microbial biomass, aggregate stability, crop yield, and nitrogen retention (Diacono & Montemurro, 2010). Combined application of HCA, mainly in the form of straw, and mineral N fertilizer turned out to be most effective in increasing SOC content and soil fertility in a range of different cropping systems, such as lowland rice (Bhattacharyya et al., 2012), upland maize (Meng et al., 2017) and wheat (Yang et al., 2017). However, a commonly used criterion for the assessment of HCA quality, the C/N ratio, has been found to be not always the best parameter for the prediction of the effects of the HCA on soil processes, especially nitrogen dynamics, but more the soil properties and the binding forms of carbon and nitrogen, i.e. the functional groups, in the HCA (Chen et al., 2014; Liu et al., 2017). Most recently, the importance of stoichiometric effects, i.e. the ratios of key elements partaking in (bio)chemical reactions, for the fundamental biogeochemical nutrient turnover processes in the soil has attracted increasing attention. For example, the ratio between dissolved organic carbon (DOC), derived from biochar, and soil inorganic nitrogen was found to play a central role in regulating soil nitrogen dynamics and especially formation of N_2O, a potent greenhouse gas (Lan et al., 2017; Feng & Zhu, 2017). The effects of stoichiometric relationships, also including phosphorus availability in the soil, on soil nutrient dynamics and their importance for improving agricultural nutrient use efficiency is a very promising research field. However, research into this topic has to deal with a large complexity due to multiple interactions between abiotic (physical and chemical) and biotic (microbial and plant) processes in the soil.

Biochar, the carbonization product of pyrolysis, has been attracting increasing attention due to its versatile functions. The high level and age (millennia) of black carbon in fertile soils such as terra preta suggested that soil application of biochar may be a promising way for both long-term carbon sequestration and soil improvement (Lehmann & Joseph, 2015). Depending on the organic feedstock and the conversion technology, the resulting char products differ substantially in their physical, chemical and biological properties (Mašek et al., 2018). One important property of biochar is its stability to degradation in the soil (Bamminger et al., 2014; Kuzyakov et al., 2014). A prolonged sequestration of carbon, however has recently been questioned by Selvalakshmi et al. (2018). More information about the comparability of different methods to evaluate the degradability of biochars is needed, and long-term experiments are required to better understand the emission dynamics of char-derived carbon in natural soils. Agronomic yield effects of biochar have been reviewed on the European level for pot experiments (Sakrabani et al., 2017) and for field trials (Verheijen et al., 2017). Most experience is available from biochar experiments conducted in tropical environments. Though there are a few published studies on experiments with biochar in temperate soils that show clear positive yield effects (Atkinson et al., 2010; Bell & Worrall, 2011), more scientific studies are required to assess the agronomic potential in temperate soils. The innovative approach of biochar "activation" to improve yield response has triggered research on various biotechnologies to produce modified biochar (Glaser & Birk, 2012). One option is a form of co-composting, delivering a nutrient enriched biochar. However, it has not been clarified yet, to which extent such activated biochars lose their stability against microbial degradation.

The response of SOC to soil use and management is a slow process that can only be evaluated with long-term experiments. Data availability is still limited. Nevertheless, available long-term studies report beneficial impacts of application of pure HCA or HCA combined with mineral fertilization on SOC stocks, physical and biological soil properties and also yields (Edmeades, 2003; Körschens et al. 2013; Maltas et al., 2018; Wang et al., 2018). There is ample evidence that compost application is generally an effective way to improve soil quality, but the growing use of new composting technologies including various additives calls for an interdisciplinary research on the effects of these technologies on soil functions, particularly their impact on the production of biomass and carbon storage (Diacono & Montemurro, 2010; Barthod et al., 2018). The same is true for the application of digestate from biogas production as organic fertilizer, for which only limited information from field studies is available (Möller, 2015).

The increasing use of various organic substrates as soil amendments imposes also new chemical risks by introducing novel compounds into the ecosystem, such as plastics (Bläsing and Amelung, 2018), antibiotics (Xie et al., 2018), disinfectants, and other pollutants. These are ingredients of products for human use, such as hormones and other human pharmaceuticals, being incidentally contained in human waste products, or perfluorinated tensides and brominated flame protection agents that accidentally reach arable ecosystems. In contrast to plant protection agents and contamination with heavy metals and other abiotic pollutants, however, there is no environmental legislation procedure, and detailed environmental risk assessment data are frequently lacking.

Contamination of soils with plastic is getting increasing attention due to the persistent nature of the materials. Mulching of soils with plastic foil is an efficient measure to increase soil temperature while retaining moisture and suppress weed growth, e.g., for specific horticultural cropping systems such as asparagus (Tarara, 2000) or specific soils (Wu et al., 2017). In Europe, 4270 km^2 of arable land are currently covered with plastic foil (Scarascia-Mugnozza et al., 2011). In China, this practice led to an input of up to 308 kg plastic ha^{-1} (Zhang et al., 2016). Much higher amounts may reach the soils as incidental part of sewage sludge and compost. Nizetto et al. (2016) assume that in Europe, for instance, sewage sludge application alone adds between 63 000 and 430 000 tons microplastics to soil annually. Data for compost are scarcer, but could comprise an annual input of 0.02 to 6 kg plastic ha-1, particularly after application of compost from municipal biological waste (Bläsing and Amelung, 2018). Investigations on the ecotoxicity of plastics in field soil is still in its fledgling stages and needs to be advanced.

Figure X3: Plastic garbage as source of soil contamination. (eigentlich nicht so passend, da es um Plastik aus landwirtschaftlichen Inputs wie z.B. Kompost geht)

Also compounds like pharmaceutical and disinfection products reach the soil that have been specifically designed to kill or at least inhibit microbial growth (see reviews by Jeschalke et al., 2014; Mulder et al., 2018). These compounds enhance the formation and selection of resistance genes already in the animal, and later on also in soil, therewith potentially contributing to the increasing emergence of multi-resistant human pathogens (Forsberg, 2012). In soil, particularly the presence of labile C sources, for instance, in liquid manure, fosters microbial growth and enhances thereby also selection of resistance genes. Different risks may arise from antiparasitics in animal husbandry, which specifically act on members of the soil faunal community and thus on related food webs. In addition, other novel priority pollutants like perfluorooctanoic and perfluorooctanesulfonic acid may have specific detrimental effects on soil faunal members such as earthworms, though their input to soil is mainly accidental and should be avoided. This avoidance is, however, frequently not applicable for pharmaceuticals and disinfectants, if their use is needed to avoid spreading of diseases, which has higher priority than soil conservation.

The recycling of nutrients such as phosphate from substances such as sludge and other waste materials in fertilizer production is a topic of research and development in academia and industry and of discussion in politics and European regulation in the frameworks of the EU Action Plan for the

Circular Economy (EC 2015) and the Raw Materials Strategy (Ekardt et al. 2015). Recycled nutrients may have different influences on soils, including its contamination with substances, such as heavy metals, depending on the original material and its treatment (Desmidt et al. 2015; Montag et al. 2015). Recent concerns about the finite character of global mineable P reserves have especially stimulated research and technology development of P recycling from sewage sludge and other waste materials. The P recycling products clearly differ in their fertilizer effects in the order of struvite (equivalent to triple superphosphate) > Mg-P = sinter-P > Ca-P from cupola slag > thermally treated sewage sludge ashes > meat-and-bone meal ash = Fe-P (Römer and Steingrobe, 2018). In addition to these materials, bone char, manufactured by a technical pyrolysis of defatted bones from slaughterhouses, can be used as a slow-release P-fertilizer, the effect of which can be improved by an "internal activation" through reduced sulfur compounds (Leinweber et al., 2018b). However, in principle all P-recycling products need to be tested for agronomic effectiveness in long-term experiments, which has not been done yet, and the legal regulations for their application are far behind the scientific and technical developments in P recycling.

Research has shown that inoculation of soils and seeds with mutualists of crops and antagonists of pests can lead to better yields and to reduced need for pesticide application. However, many results, especially on microbial products, are from laboratory experiments, and results for those products under field conditions are still scarce.

The promotion of important functional traits of the soil microbiome via targeted inoculation of soil with bacteria or fungi has been proposed since more than 150 years (for reviews see Triplett and Sadowsky, 1992, and Mahmood et al., 2016). However, the success of microbial inocula to soil has been discussed controversially in the literature, as results were in many cases strongly depending on site specific conditions like soil type, climatic conditions and overall agricultural management, even if microbial symbionts had been applied, which form very specific interactions with the plant (Roberts et al., 2017). In many cases the introduced microbes were outcompeted by the soil microbiome, and an establishment of the new microbes was not possible due to missing ecological niches and missing adaptation of the inoculum to the site-specific environmental conditions. Even in cases where an improvement of plant growth has been described, effects were often not sustainable and there was a need for repeated inoculations, indicating that a stable integration of inocula into the core microbiome of soils is difficult to achieve. Thus, future approaches must be more linked to develop approaches for a sustainable inoculation of plant-beneficial microbes to soils using existing bacterial or fungal strains, than isolating new microbes with comparable properties. Recent approaches using technologies where the inoculum has been applied to soil using carrier materials have been promising, as the carrier material gave the inoculum an artificial (temporal) niche in soil after application and protected the introduced microbes from grazing and competition with the autochthone microflora of soils (for review see Malusa et al., 2012). These techniques must be further developed including the use of waste materials to ensure a most effective use of natural resources in an environmental friendly manner. Another possibility is using nematodes as carriers for bacterial inocula. For example, the entomopathogenic nematodes (EPN) of the genera Heterorhabditis and Steinernema are symbiotically associated with bacteria of the genera Photorhabdus and Xenorhabdus, respectively. Thus, already 20 years ago the idea was born to use nematodes as a possible vector for inoculation (Hominick et al., 1997). However, despite being highly successful in several laboratory studies, for the practice there is a big research challenge as both nematodes and bacteria need to be cultivated and brought to soils.

Even if most inoculations have not been sustainable, it needs to be considered that any introduction of living microorganisms to soils bears the risk that those microbes can develop their own dynamics in soil. Thus, particular care must be taken when choosing new inocula that the selected microbes are not (facultative) pathogens for humans or animals (e.g., Hirneisen et al., 2012).

Using inoculants, such as EPN, directly as antagonists against soil-borne pests, such as the Western corn rootworm (Diabrotica virgiefera virgiefera), is a promising strain of research (Johnson et al. 2016, Kergunteuil et al. 2016). The sustained establishment of the inoculants in the soil is in most cases not the aim, but the substitution of pesticide application. Although some research on effects on non-targeted organisms is still needed, in general negative effects are much less expected than from chemical pesticides (Kergunteuil et al. 2016). However, there are still technical and economic obstacles for the wide application of antagonists against soil-borne pests, and research, including industrial research, currently seems to be the decisive driver towards inoculating soils with natural enemies of pests.

The concern about detrimental effects of microbes in the soil is especially justified with respect to the use of wastewater for irrigation purposes, which has been banned in many countries in the last decades for health reasons, but which has recently been reconsidered as an important irrigation source in areas with water scarcity. This may become relevant in Germany as well, in view of the expected increase in irrigation demand due to climate change in Germnany (e.g. Riediger et al. 2016) and Europe (Hamidov et al., 2018). Irrigation can be beneficial for soil functions, if it is done well, but can also severely damage them. There is an increasing awareness that the introduction of high loads of fecal microbes and bacteria with wastewater irrigation, which are resistant against antibiotics, may cause problems both for human and environmental health. Although first assessments and strategies for a wastewater irrigation have been defined (e.g. Seis et al. 2016, EC 2018), which include the use of pretreated wastewater in the future, further research on the activity and fate of introduced, potentially harmful microbes, is mandatory.

There is a strong trend towards developing technologies for higher precision in applying fertilizers and pesticides. Especially for pesticides a reduction of application rates and for fertilizers higher N-efficiencies are expected to result from this. Putting the potential into practice depends, among others, on soil and agricultural researchers to improve soil maps and develop procedures and algorithms (Techen and Helming 2017).

It is well known that conventional uniform management of fields creates yield losses due to insufficient inputs to some parts of the fields, while other parts receive excessive inputs, which wastes resources, degrades the soil and pollutes the environment (Whelan & McBratney, 2000). This problem can be solved by site-specific soil management in precision agriculture (Gebbers & Adamchuk, 2010). Despite the fact that implements for variable fertilization, tillage and spraying are available, the adoption and success rate of precision agriculture in Germany is low (Busse et al., 2014). The main reason for this is that farmers in Germany cannot obtain maps of relevant soil attributes with sufficient spatial density and accuracy at reasonable costs. Sensitivity analysis of the system of site-specific fertilization shows that sampling density is the most relevant factor for precise application of inputs (Gebbers & De Bruin, 2010; Schirrmann et al., 2011). For example, sampling intervals of about 18 m are required to capture spatial differences in variable quaternary sediment soils. However, bulk sampling over a 1 ha grid is what ambitious farmers find acceptable while best management practices in Germany recommend sampling on just a 5 ha grid. The high costs for soil sampling and laboratory analyses not only prevent a higher spatio-temporal resolution of soil monitoring (Whelan & McBratney, 2000), but also lead to the use of rather simple recommendation algorithms based on very few soil properties as inputs (Jordan-Meille et al., 2012). The demand for a multitude of input variables is one of the main reasons why research results on soil nutrient dynamics have been only incompletely adopted yet in practice (Wallor et al., 2017). For example, existing knowledge on subsoil processes is not taken into account in the best fertilization practices since farmers cannot afford the costs for sampling and soil analysis (Jordan-Meille et al., 2012). From this situation we derive three interconnected research challenges for site-specific soil management: a) Development of methods that provide relevant soil data timely and cost-effectively at high spatial and temporal resolution; b) Evaluation of these new soil data by adaption of existing dynamic soil models and/or use of machine learning methods; c) Embedding the management of these complex data and algorithms into an accessible decision-making framework for farmers and agricultural service providers which regards agronomic and socio-economics aspects (Lawson et al., 2011).

Precision is not only relevant in terms of the spatial distribution of fertilizers but also in terms of the basic determination of fertilizer demand contingent on the soil status. Specifically, in regard to soil, there is great potential for improved P-fertilizer recommendations. Only recently, more accurate, soil pH-dependent equations for estimating the content of plant-available P have been derived from long-term fertilizer experiments to transform the values of the various established P extraction methods into each other and enable better general assessments of P fertility of soils in Germany (van Laak et al., 2018). Furthermore, P-dependent crop yields are determined not only by plant-available P in the soil, but also by soil pH value, SOC content, type of P fertilizer, and crop type/variety, whereas the exact amount of P fertilizer is less important (Buczko et al., 2018). These newly detected and mathematically described relationships need to be tested under practical conditions but generally may offer considerable potential of reducing the overall P fertilizer applications along with a wide range of other approaches to reduce P input and thereby environmental impacts of excess P inputs to soil (Leinweber et al., 2018a).

4. Cross-cutting research challenges

Complementary to the specific soil research needs as outlined in chapter 3 there is a need for cross-cutting research activities to make soil knowledge operational for decision making in practice and policy. This includes an integrated approach of natural and socio-economic sciences to understand conditions and constraints of implementing sustainable soil management practices. Soil process knowledge needs to be synthesized to metrices and indicators to allow for the assessment of emerging technologies and associated soil process changes on environmental risks and benefits, economic costs and benefits, and social targets such as human health, ethics and equity. Knowledge about these impacts is a prerequisite for the development of policies and other governance instruments that facilitate adoptions of sustainable soil management practices through financial incentives and/or leveraging behavioral changes. Such management and governance recommendations need to integrate stakeholder perspectives and build upon simulation models across geo-biophysical and socio-economic conditions. Basic support for this is brought by sophisticated data repositories allowing for reuse and recombination of soil research data, particularly those from long term experiments. These elements are briefly outlined below.

Data management

Scientific databases have been recognized as a crucial part of the science system's infrastructure (OECD 2007). With the INSPIRE directive, the EU has established an infrastructure for geo-spatial data collected by government organizations, which are essential for soil and agricultural research (INSPIRE 2007). Since the management of research data is still often project-based, the establishment of a "National Research Data Infrastructure" for Germany was recommended by RfII (2016) and implemented by GWK (2018). Such a national initiative may be a good complement to the "European Open Science Cloud" planned at European level (EU 2018).

Although research data infrastructures are still under construction, the FAIR principles (data are Findable, Accessible, Interoperable, Reusable) provide a generally accepted basis for the management of research data (Wilkinson et al. 2016, Hodson et al., 2018). Further development of the research data infrastructure should be science-driven and take into account the specifics of the different scientific disciplines (RfII 2016, DFG 2018). Soil and agricultural scientists and respective organizations (e.g., "global soil partnership" (GSP), "global open data for agriculture & nutrition" (GODAN), "world soil information" (ISRIC), "agricultural model intercomparison and improvement project" (AGMIP)) are well represented at the Research Data Alliance (RDA), a platform for the self-organization of scientific communities (https://www.rd-alliance.org/). RDA is a good place to discuss progress on standards, ontologies, data semantics, metadata, data policy and method development (Svoboda et al. 2018, Hoffmann et al. 2018).

Method development in the areas of data mining, artificial intelligence, big data and linked data is becoming increasingly important in agricultural and soil sciences (e.g. Section 3.2). Technological advances and the increasing digitization in agriculture and thus the increasing importance of data and their processing are expressed in the term smart farming. Big data analysis is not yet widely used in agriculture, but there is great potential in smart farming, not only in primary production but in the entire food supply chain (Kamilaris et al. 2017, Wolfert et al. 2017). A key issue for big data applications with agricultural and soil data is data-ownership, value of data, privacy and security. The agricultural technology providers, which operate their own cloud platforms, play an important role in this context. On the one hand there is the development to closed, proprietary systems and on the other hand to more open systems, which are based on open standards and interfaces (Kamilaris et al. 2017).

Research in the soil and agricultural sciences makes use of a wide variety of data, e.g. laboratory data, logger data, field observations, landscape monitoring, genotype data, phenotype data, spectrophotometer data, sensor data, images etc. New data sources, like mobile technology, crowdsourcing and remote sensing, are achieving maturity for agricultural applications (Janssen et al. 2017). The particular challenge in managing the diverse and heterogeneous soil and agricultural research data is to achieve interoperability through standardization.

Since soil processes are typically associated with very long time scales, special emphasis needs to be given to long-term field experiments (LTFE) as data sources. LTFE, of which some trials have been carried out for more than 100 years, deliver important information for answering current and future questions on soil use, -productivity and, not least, for future food security. Notwithstanding the high demand for data from long-term field experiments, these data are scattered or only partly available in an adequate form. In particular, the availability and standardization of long term field experiments has great potential for scientific applications (Berti et al. 2016, Perryman et al. 2018, Grosse & Hierold 2017).

Exploiting modern data capture, transfer and analysis technologies could improve land management practices and permitting a more nature based approach to industrial and organic methods of farming (Nathanail et al. 2018).

Modelling

As an important prerequisite for including soil functions in sustainability assessment and science based decision support, the impact of soil management on soil functions need to be quantified. It is a widely shared conception that soil functions are systemic properties emerging from a myriad of complex process interactions going on in soil (Vogel et al. 2018). Moreover, these soil functions cannot be measured directly by sensors but need to be derived from observable proxy variables in the sense of suitable indicators (Dominati et al. 2014, Rutgers et al. 2012). However, even if such indicators can be found, it is a major challenge to predict their dynamics in response to changes in soil management, which is actually required to assess management options in terms of sustainability targets.

A reliable prediction of the impact of future developments in soil management requires a profound understanding of how soil systems actually work since empirical data are typically missing when dealing with new developments such as climate change or the development of new technologies. Hence, the dynamics of soil functions needs to be predicted based on profound knowledge of the underlying processes. This requires a mechanistic model approach linking the relevant physical, chemical and biological processes including their interactions. Such a systemic approach may allow for the simultaneous modelling of various soil functions in response to external perturbations brought about by soil management (Vogel et al. 2018). A major challenge is to identify the appropriate level of complexity. Since a detailed representation of soil processes at the molecular scale within soil as a highly heterogeneous physical environment is not realistic, we need to identify interactions and intrinsic soil properties at a higher level integrating small scale processes in an appropriate manner. Candidates for such properties are e.g. soil organic matter, bulk density and pH, which are often used as indicators for soil functions (e.g. Rutgers et al. 2012). The required level of complexity for modelling these “soil functional characteristics” (Vogel et al. 2018) is a formidable challenge for future research.

For example, it is an open question in how far we need to consider microbial diversity in soil to model nutrient use efficiency of plants or the turnover of organic matter. There is some evidence that the enormous functional diversity of soil organisms may allow for simplifying diversity and to describe the microbial communities as a whole (Nannipieri et al. 2017). Other processes might be found to require a higher level of complexity than previously thought. Modelling the effect of crops, crop rotations and catch crops on soil structure especially in the subsoil (as discussed in chapter 3.2) requires some knowledge on the capacity of plant roots for structure formation or their tendency to reuse existing pores. This is also required when modelling the recovery of soils after compaction (as discussed in chapter 3.3) which also needs to reflect the importance of bioturbation and swell-shrink processes on structure formation. These are just a few processes that are deemed to be important at the level of soil functions from a bottom up perspective but not yet included into typically used models.

From a top down perspective asking what models are required to evaluate measures taken to achieve sustainability goals, makes the need for a systemic model approach obvious. For example, the reduction of pesticides does not just protect useful insects it has implications for soil tillage practices and the design of crop rotations with possible effects on soil structure, the soil biome as well as the carbon and nutrient budget. Moreover, all this depends on the local site conditions in terms of soil type and climate. Similar scenarios can be made up for other sustainability targets such as the '4 per 1000' initiative as described in chapter 3.4. In summary, accounting for all these interactions in terms of external management and internal soil processes to predict the impact of soil management on soil functions is one of the major challenges in soil system modelling. To set up and drive such models there is an urgent need for geo-spatial soil data and research data on soil processes both from lab and field experiments and especially from long term field trials.

Sustainability assessment, economics, and governance

The sustainability assessment of soil management can reveal the relevance of soil processes and functions in the wider societal context beyond the production of biomass. Keesstra et al. (2016) have outlined the fundamental role of soils for the United Nations Sustainable Development Goals (General Assembly, 2015) through their contribution to food provision (SDG2), climate change mitigation via carbon sequestration (SDG 13), supporting ecosystem services and biodiversity (SDG

15) and resource efficient production (SDG12). Ecosystem services and resource use efficiency are two concepts to operationalize the causal link between soil functions and sustainability targets at different spatial and decision making levels (Helming et al., 2018). While the concept of ecosystem services is already well established (Haines-Young and Potschin, 2013) the role of soil functions therein is still not yet well conceptualized (Baveye et al., 2016). The same is true for resource use efficiency, which, albeit being the key concept behind the sustainable intensification paradigm (Rockström et al., 2017), does not yet sufficiently account for the role of ecological processes in the soil and at the soil-root interface for more efficient utilization of the key resources water, energy, nutrients (Struick et al., 2014). For example, the role of catch crops, crop rotations and crop diversity for optimizing nutrient use efficiency in soil through root architecture and functional traits has yet to be understood and formalized with indicators for resource efficiency assessment. Different choices of soil management practices and crop rotations affect greenhouse gas emissions (Peter et al., 2017) and energy use efficiency (Arodudu et al., 2017), but are hardly accounted for in current assessments of climate mitigation potentials in agriculture. The increasing use of recycled material and waste water for fertilization, irrigation and soil amendments is promising in terms of improving resource use efficiency. However, the associated impacts of introducing waste material (plastics), organic pollutants (antibiotics) and (micro)organisms into the soil system on environment and human health is not well understood. Risk assessments need to be established that build upon the precautionary principle and that can inform legislation on the utilization of recycled and newly developed substances brought into the soil.

The potential of soil carbon sequestration for climate change mitigation has become prominent with the ‘4 per 1000’ initiative (https://www.4p1000.org/), its realization under competitive agronomic conditions is a tremendous research challenge. The cost efficiency of such services is a key prerequisite for its implementation at farm level. While soil is a private good, many of the soil related services such as climate change mitigation are public goods. The farmer is only paid for the yield that is brought to market and not for the other ecosystem and climate services, which the soil provides.

The remuneration of such services would compensate for possible yield losses associated with the implementation of soil improving management, thereby making it economically feasible for the farmers. Such payments for ecosystem services (Schomers and Matzdorf, 2013) are increasingly promoted as innovative governance instrument. It however requires the (monetary) valuation of soil ecosystem services, an approach that is not yet well established and for which data are hardly available (Jonsson et al., 2017).

Many of the soil improving practices do only pay off at long term, and such long-term benefits are difficult to monetize and account for in cost-benefit analyses. The socio-economic awareness of practices such as subsoil loosening is not yet well established (Hinzmann et al., submitted). Here, property rights are an important factor because farmers tend to pay less attention to longterm soil quality on rented land than on their own property unless specific stipulations about soil quality maintenance are established in land tenancy agreements (Lichtenberg, 2007). Data about the conditions and success of such private governance instruments is however rare (Daedlow et al., 2018).

Public policy for sustainable soil management has to incentivize particularly those ecological intensification practices that reinforce the inherent capacity of soils to produce biomass (Titonell, 2014), without endangering the provision of other soil services. Yet, governance of soils – formal policies and informal governance – is often interwoven with other policy and societal objectives, so that conditions for soil-related governance are less well understood than those for water or biodiversity (Juerges & Hansjürgens, 2018; Turpin et al. 2017). Whereas a combination of regulatory and incentive-based governance instruments is promoted (Kibblewhite et al., 2012), a better understanding of the optimal and spatially more sensitive instrument mixes is needed (Juerges et al., 2018). This includes transformation from land-ownership based subsidies to result-oriented schemes that consider the common welfare or a revision of spatial planning regimes (Bartkowski et al., 2018; Moroni, 2018) in as much as investigating and unleashing the potential of informal governance instruments (e. g. Price and Leviston, 2014).

Stakeholder interaction

New knowledge and adapting decision-making to address sustainability challenges requires the interaction with actors from outside academia in research (Lang et al., 2012) also in soil science (Bouma, 2001). Stakeholder interaction is a key towards understanding actual knowledge demands (Bartke et al., 2018) and strengthening the science-policy-society interface to facilitate knowledge-based development and implementation of land-use practices (Rounsevell et al., 2012). To prevent disillusionment and drawbacks, effective stakeholder interaction must define carefully the objective (information, consultation, knowledge co-production and empowerment – Enengel et al., 2012) as well as selection of relevant stakeholders and methods for the interaction in the specific disciplinary and geographical context (Reed 2008). As Reed (2008) emphasizes, there is no simple "tool-kit" for interaction yet. Soil scientists need to take stakeholder engagement serious early on and systematically so that the process enables empowerment, equity, trust and learning. Strategic land-use and soil management research demands identified recently (Nathanail et al., 2018) emphasize the stakeholders' role in understanding values of ecosystem services in land-use decisions, effective and efficient land-use planning and decision making and the design of mechanisms for effective knowledge transfer to policymakers and land managers.

5. Synthesis

Emerging soil management practices evoke soil research challenges, as well as cross-cutting research challenges. We have assessed research challenges along four categories of soil management changes and a cross-cutting category for Germany as an example of countries with temperate climate, high technological development level and low yield gaps.

Concerning spatial arrangements of cropping systems, key research challenges address agroforestry and intercropping systems, which may become more important in the future because of an increasing demand and technological development, but also driven directly by research itself by uncovering benefits and management details. Research needs are on nutrient response efficiencies, nutrient retention efficiencies and water consumption at the field scale in agroforestry systems as compared to conventional agriculture. Also the effectiveness of agroforestry to reduce soil erosion and related C sequestration as well as resource competition in intercropping systems are key research challenges in this area.

Key research challenges concerning crops and rotations are seen especially in the area of root architecture and functions, as well as improved understanding of the soil-rhizosphere microbiome. The expected insights may lead to better combinations of crops and crop varieties with certain management practices and environmental factors, and to accordingly improved crop varieties through targeted breeding activities. Similarly, the better understanding of benefits and consequences of crop diversification could inform farmers on how to best diversify when factors external to research drive crop diversification.

For mechanical pressures, key research challenges address compaction such as the spatial prediction of actual compaction risk and effects of compaction on soil-plant-atmosphere interactions based on a systemic approach. Especially, farmers' decision-making could be well influenced with new insights from this research, when combined with new technologies for decision-support, which would show farmers the compaction risk and potential long-term yield effects of different management options. Additionally, research on the recovery and amelioration of compacted subsoils is deemed crucial for improving soil functions on already affected soils.

To assure that societal goals, for instance carbon sequestration, may be implemented sustainably, key research challenges for inputs into the soil have been identified such as the quantification of above- and belowground carbon input by different crops and varieties in long-term experiments, not just for carbon sequestration but mainly to improve soil organic matter management. Effects of stoichiometric (C:N:P) relationships on soil nutrient dynamics and nutrient use efficiency as well as long-term agronomic effectiveness of P-recycling products as well as ecotoxicity of plastics and pharmaceuticals in soil gain relevance in terms of resource scarcity and circular economy strategies leading potentially to increased use of organic waste or products thereof. Advancing biotic inoculation methods towards sustainable field applications is one of the research challenges which presents an area where research itself has been identified as the main potential driver of soil management changes towards improved soil functions.

Rising food demand as well as bioeconomy strategies around the world call for sustainable intensification of agricultural production (Garnett et al. 2013). For soils this means that the production function of soils has to be increased while keeping the other soil functions stable or improving them. The emerging soil management practices addressed in the identified key research challenges, offer mainly opportunities, and few threats to soil functions. We have synthesized results of this study into the formulation of key research challenges, which we assessed regarding their relevance for the five soil functions (Figure 3) and for soil threats describing key soil degradation processes (Figure 4). The perspective of soil threats widens the foresight perspective in direction of risks associated with soil management. Out of the soil threats defined in Thematic Strategy for Soil Protection of the European Commission (EC 2006) the following are seen relevant to our study: wind and water erosion, compaction, organic matter decline, soil biodiversity decline and soil contamination. We have excluded soil sealing, floods and landslides because they are less relevant in agricultural soil management at field scale. We have also excluded salinization because this is not considered a soil threat at the climatic and soil conditions in Germany (Stolte et al. 2016).

		(Hypothetical) Relevance for soil functions				
Chapter	Key research challenges – Research is needed on:	Production of biomass	Storing and filtering water	Storing & recycling of nutrients	Habitat for organisms	Carbon storage
3.1 Crops and rotations	Root architecture and functions	++	+	+++	++	+++
	Benefits and consequences of crop diversification					
	Improved understanding of the soil-rhizosphere microbiome					
3.2 Mechanical Pressures	Spatial prediction of actual soil compaction risk and identification of soil compaction patterns	+++	+++	++	++	+
	Effects of soil compaction on soil - plant - atmosphere interactions based on a systemic approach	+++	+++	++	++	+++
	Recovery and amelioration of compacted subsoils	+++	+++	++	+	+
3.3 Inputs into the Soil	Precise quantification of above- and belowground carbon input by different crops/varieties in long-term exerperiments to improve SOM management	++	++	++	++	+++
	Effects of stoichiometric (C:N:P) relationships on soil nutrient dynamics and on agricultural nutrient use efficiency	+++	+	+++	+	+
	Ecotoxicity of plastics and pharmaceuticals in soil	++	++	0	++	0
	Long-term agronomic effectiveness of P-recycling products	++	0	+++	0	0
	Sustainable biotic inoculation methods for field application	++	0	+++	++	0
Ch. 3.4	Nutrient response efficiencies and nutrient retention efficiencies in agroforestry systems and conventional agriculture under comparative conditions	++	+++	+++	+	+
	Water consumption at the field scale of agrofrestry and conventional agriculture under comparative conditions	++	+++	+	+	+
	Effectiveness of agroforestry to reduce erosion and related C sequestration	+	++	++	+	+++
	Resource competition in intercropping systems	+++	++	+++	+	+

Figure 3: Key research challenges and their (hypothetical) relevance for soil functions. [Später gibt es die graphische Variante. Änderungen können in der Excel-Datei vorgenommen werden oder hier einen Kommentar einfügen.]

		(Hypothetical) Relevance for Mitigation of Soil Threats				
Chapter	Key research challenges – Research is needed on:	Mitigation of Erosion	Mitigation of Compaction	Mitigation of organic matter decline	Mitigation of soil biodiversity decline	Mitigation of soil contamination
3.1 Crops and rotations	Root architecture and functions	?	?	?	?	?
	Benefits and consequences of crop diversification	?	?	?	?	?
	Improved understanding of the soil-rhizosphere microbiome	?	?	?	?	?
3.2 Mechanical Pressures	Spatial prediction of actual soil compaction risk and identification of soil compaction patterns	+++	+++	++	++	0
	Effects of soil compaction on soil - plant - atmosphere interactions based on a systemic approach	+	++	+++	+++	0
	Recovery and amelioration of compacted subsoils	0	+	+	+	0
3.3 Inputs into the Soil	Precise quantification of above- and belowground carbon input by different crops/varieties in long-term exerperiments to improve SOM management	+	++	+++	++	+
	Effects of stoichiometric (C:N:P) relationships on soil nutrient dynamics and on agricultural nutrient use efficiency	0	0	0	0	0
	Ecotoxicity of plastics and pharmaceuticals in soil	0	0	0	++	+++
	Long-term agronomic effectiveness of P-recycling products	0	0	0	0	+
	Sustainable biotic inoculation methods for field application	0	0	0	+	0
Ch. 3.4	Nutrient response efficiencies and nutrient retention efficiencies in agroforestry systems and conventional agriculture under comparative conditions	+	+	++	+	+++
	Water consumption at the field scale of agrofrestry and conventional agriculture under comparative conditions	+	+	+	+	++
	Effectiveness of agroforestry to reduce erosion and related C sequestration	+++	++	+++	+	++
	Resource competition in intercropping systems	++	+	++	+	++

Figure 4: Key research challenges and their (hypothetical) relevance for soil threats. [Später gibt es die graphische Variante. Änderungen können in der Excel-Datei vorgenommen werden oder hier einen Kommentar einfügen.]

Except for one of the identified key research challenges all have been identified as being relevant for all of the five soil functions (Figure 3). This illustrates the systemic relationships between soil management practices and affected soil processes. These complex interrelations challenge research and hinder the formulation of simple management recommendations from the soil perspective. Still, most key research challenges have been assessed to be more relevant for the three soil function "production of biomass", "storing and filtering of water", and "storing and recycling of nutrients" than for the remaining two functions "habitat for organisms" and "carbon storage". Those first three functions are also those that immediately determine plant growth. Their optimization is therefore decisive for realizing the otherwise vague concept of sustainable intensification through the activation of the soil inherent capacity to make water and nutrients available and accessible for plant growth. The relevancy of key research questions for the mitigation of so called soil threats has been assessed to be more diverse (Figure 4). Some key research questions are relevant for (almost) all soil threats, especially the research challenges on agroforestry and intercropping. Others were assessed to have little relevance for mitigating soil threats, especially in the category of inputs into the soil, while the strengths of these research topics lie in the promotion of production oriented soil functions.

[Passage about research challenges along three spatial scales, namely large field to landscape scale (100-1000m), within field scale (1 -100 m), plant/root scale (0.1- - 1 m^3), to be written after the holidays]

While the specific soil research topics are crucial for advancing sustainable soil management and sustainable intensification, the cross-cutting research challenges (Figure 5) address the need for synthesis, generalization and up-scaling of research results to make the knowledge accessible for a wide range of decision support. Availability of data is decisive for fulfilling such tasks and it is an important research challenge to manage the diverse and heterogeneous soil and agricultural research data, including data from long-term field experiments, to achieve interoperability through standardization. Also modern data capture, transfer and analysis technologies open up the challenge to exploit research data to improve soil management practices towards sustainability. Furthermore, since soil functions are integral properties emerging from a multitude of complex process interactions we need complex soil models that are embedded in a systemic approach to address the impact of soil management on soil functions. Research challenges are also seen in comprehensive sustainability assessments that put soil research results into a broader societal context, including the United Nations Sustainability Goals. The concepts of ecosystem services and resource efficiency are deemed useful to study societal relevance of soil functions but need supplementation, for instance in the direction of human health. Also the assessment, economics and governance of sustainable soil management require an interdisciplinary approach involving socio-economic and natural science expertise as well as stakeholder interaction. Systematic stakeholder engagement is a crucial challenge along the whole chain of research to enable sustainable soil management.

Key messages for cross-cutting research

The concept of ecosystem services and of resource efficiency need to be applied to study societal relevance of soil functions.

The assessment and governance of sustainable soil management requires an interdisciplinary approach involving socio-economic and natural science expertise.

Since soil functions are integral properties emerging from a multitude of complex process interactions we need systemic modelling approach to address the impact of soil management on soil functions.

Managing the diverse and heterogeneous soil and agricultural research data, including data from long-term field experiments, to achieve interoperability through standardization is a particular challenge.

Early on systematic stakeholder engagement is crucial to enable empowerment, equity, trust and learning.

Figure 5: Key messages for cross-cutting research.

6. Conclusions

Agricultural soil management develops over time, driven by socio-economic, biophysical and technological factors. Soil research needs to react on this by identifying soil research challenges, tackling these challenges with systemic and interdisciplinary research including the use of long-term field experiments, and generating decision support. We have assessed such research challenges for four categories of agricultural soil management changes for Germany as an example of high technological development with low yield gaps in a temperate zone and with a time horizon of up to 20 years. As an interdisciplinary author group involving a large spectrum of soil research in Germany, we have done a broad assessment covering a range of important research challenges. However, the study was not meant to, and cannot be, comprehensive. Some important aspects could not be covered, such as the functional role of soil fauna and how it is affected by soil management. Also the research challenges may differ in other climatic zones or where the focus is less on arable and more on grassland soils.

While the concept of sustainable intensification poses a challenge for agricultural production in general and options for its realization are still vague, our results show potential for the implementation of sustainable intensification in the context of soil management. The assessment shows that the implementation of the soil research challenges can contribute to increasing the production oriented soil functions and keeping the other functions, such as the habitat for organisms function, at least stable or improving them as well.

This way, this first overview of soil research challenges in response to emerging soil management practices provides an information base for integrated endeavors of agronomists and soil scientists, as well as other researchers, to support the development and the optimal implementation of practices and technologies to maintain soil functions and realize a sustainable intensification.

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