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 functions. Triggered by biophysical constraints as well as rapid structural and technological developments, new management practices are emerging with largely unknown impacts on soil processes and functions. This impedes assessments of the potential of such emerging practices for sustainable intensification, a paradigm coined to address the growing demand for food and nonfood products. In terms of soil management, sustainable intensification means that soil productivity is increased while other soil functions and services, such as carbon storage and habitat for organisms, are simultaneously 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 functions.

We distinguish four categories of soil management practices: spatial arrangements of cropping systems, crops and rotations, mechanical pressures, and inputs into the soil. Key research needs identified for each include nutrient efficiency in agroforestry versus conventional cropping systems, soil-rhizosphere microbiome elucidation to understand the interacting roles of crops and rotations, the effects of soil compaction on soil–plant–atmosphere interactions, and the ecotoxicity of plastics, pharmaceuticals and other pollutants that are introduced into the soil. We establish an interdisciplinary, systemic approach to soil science and include cross-cutting research activities related to process modeling, data management, stakeholder interaction, sustainability assessment and governance. The identification of soil research needs from the perspective of agricultural management

facilitates cooperation between different scientific disciplines in the field of sustainable agricultural production.

Contents

1. Introduction

Modern agriculture is highly productive and provides resources and services that are critically important for humanity. However, many current agricultural production techniques undermine the long-term viability of ecosystems and their services (Foley et al., 2011). Current worldwide bioeconomy strategies threaten to exacerbate this so-called 'land use dilemma' even further, striving to substitute fossil 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; Foresight, 2011; Godfray and Robinson, 2015; Kastner et al., 2012), a higher demand for biomass is implied. However, fulfilling this demand sustainably requires soil management that increases the production function of soils while maintaining or even improving other soil functions and services, such as 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 generated profound knowledge on soil properties and processes relevant for soil management, crop growth and the multifunctionality of soils. However, huge knowledge gaps remain regarding the interaction between soil management practices, soil process responses and their effects on soil functions and ecosystem services (e.g., Key et al., 2016; Poesen, 2018; Smith et al., 2015).

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. In addition to the increasing demand from production on agricultural soils, other factors drive changes in agricultural soil management. These are socioeconomic 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 increasing demand from the bioeconomy. Changed crop varieties may occur, e.g. due to changing environmental factors and new breeding techniques. Technological developments may drive changes in field traffic. In addition, more contaminants from organic fertilizers or fertilizers from recycled nutrients are possible due to resource efficiency and circular economy strategies (Techen and Helming, 2017).

An interdisciplinary team of researchers focusing on the soil system is therefore required to understand research challenges arising from emerging agricultural practices and to improve soil process understanding, synthesize the scientific knowledge into modeling and assessment and 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, such an interdisciplinary group of researchers jointly formulated key research challenges addressing the interplay between emerging agricultural management practices and soil processes. We have structured the research challenges along four categories of soil management, namely, i) spatial arrangement of cropping systems, ii) crop choices and crop rotations, iii) mechanical pressures and iv) inputs into the soil. By formulating research challenges along the soil management categories, we follow a systemic approach integrating across biological, physical and chemical aspects of soil sciences, 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 a temperate climate, high technological development level and low yield gaps, for which Germany is an example. The temporal focus encompassed the next five to ten years with outlooks of up to 20 years, which is longer than the ordinary research project lifetime and allows for innovation to occur. It is also short enough to address perceived signals about emerging agricultural soil management practices, and it is 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 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 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.

The author group represents specific expertise in the field of soil chemistry, soil biology, soil physics, soil mechanics, soil ecology, soil biogeochemistry, soil microbiome research, horticulture and agronomy. For the cross-cutting perspectives, the group additionally includes expertise on soil modeling, sustainability assessment and agricultural as well institutional economics.

2.2 Structural Framework

The results of a foresight study about emerging soil management practices in Germany (Techen and Helming, 2017) were used as the structural framework for this paper. The foresight study analyzed 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, modeling, agricultural technologies), from authorities (policy, administration) and agricultural practice (Techen and Helming, 2019).

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. In this paper, however, we focus exclusively on the analysis of qualitative changes, because they are anticipated to have larger implications for soil processes and changes in soil functions than purely quantitative changes in 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 nutrient 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-analysis studies. It involves the development of simulation models for a comparative assessment of alternative soil management options. Modeling 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 regard 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 interactions to assure the practical usefulness of the research results.

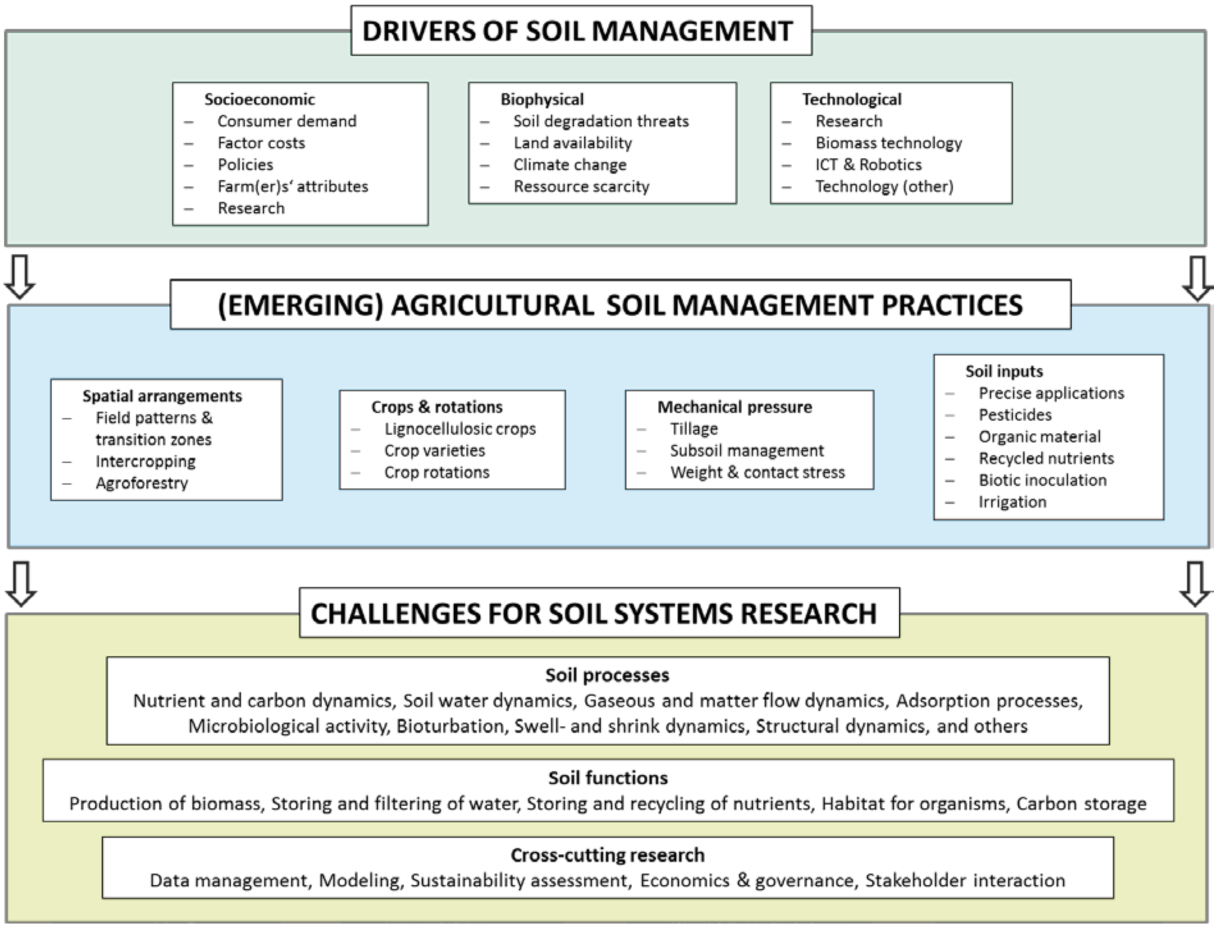

Figure 1: Structural framework for the identification of soil research challenges: socioeconomic, biophysical and technological drivers (top) affect soil management in four categories of soil management (middle). These in turn affect soil processes and soil functions (bottom), for which research challenges are formulated. Purely quantitative changes in 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 sections 3 and 4. The respective experts among the authors of section 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 6). In addition, Figure 7 presents the same key research challenges and their estimated potential influence on soil threats. A scale of 0 to 3 is used. The assessment is illustrated using a graphical style to underline that the assessment is qualitative and that there is connectivity among the soil functions and among the threats. The cross-cutting research challenges (Figure 8) were not assessed in terms of soil functions and soil threats since they are by default relevant for the whole spectrum of soil functions and threats.

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

In the following section 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 section 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 (Haenke et al., 2014; Médiène et al., 2011), the latter affecting the need for pesticide application. Currently the trend towards larger fields and eliminating landscape elements is still ongoing, triggered by large machinery sizes and the need for time-efficient management activities. In the coming 15 to 20 years, however, this trend may reverse, and it is very possible that farming machinery will become smaller (Techen and Helming, 2019). This phenomenon would not necessarily result in smaller field structures but it would ease the implementation, for instance, of policy measures to support smaller structures. Research has increasingly shown that agroforestry and intercropping, as cropping systems with smaller scaled patterns and more transition zones, can have multiple benefits, also in temperate regions (Gou et al., 2016; Pelzer et al., 2014; Smith et al., 2013; Torralba et al., 2016; Yu et al., 2015). 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. Technological improvements in the use of lignocellulosic feedstocks for energy and industry could also support a trend towards agroforestry by raising demand for woody crops and offering long-term contracts.

In general, growing trees with crops or growing two functionally different crops together will be beneficial when the tree component or the second crop acquires resources (water, light or nutrients) complementary to the other crop, but it will not be beneficial if both components are competing for the same resources (Cannell et al., 1996). Agroforestry systems are hypothesized to exhibit more efficient use of soil nutrients because tree roots can act as a 'safety net' for leached nutrients (Lehmann et al., 1998), 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, however, research on these mechanisms in temperate agroforestry is very limited. 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., 2009). 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 a short rotation coppice for bioenergy production, potential competition for resources by the tree strips are controlled every few years when the aboveground biomass is 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 that 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) and 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 with monocultures (Quinkenstein et al., 2009). 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 phenomenon has also been demonstrated by higher soil carbon levels in tree alleys compared with 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 with conventional agriculture. However, under which (soil) conditions and how to adjust management to improve nutrient use and retention efficiencies of 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 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 the 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 the provision of shade. Such microclimatic effects can have positive or negative effects on crop growth (Cleugh, 1998; Kanzler et al., 2018) 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 study 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 for the significant reduction of soil water erosion by integration of tree alleys. For example, tree alleys have higher water infiltration rates than adjacent crops, significantly reducing the 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 the retention of suspended sediment particles (Christen and 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 modeling 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 (Doetterl 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 the establishment of agroforestry systems will stimulate the 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, no research has been conducted to quantify how agroforestry affects landscape-scale carbon budgets through erosion and sedimentation.

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

In intercropping systems, crops typically alternate in strips, with a strip width ranging from several plant rows to several meters, which 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 and 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 systems (e.g., C3-wheat and C4-maize) also show considerable increases in the land equivalent ratio (LER: the ratio of the area under monoculture cropping to the area under intercropping that is needed to provide an equal yield under the otherwise same management), which appear to take advantage of temporal niche differentiation (Yu et al., 2015). Although the literature shows that intercropping can have advantages for yield stability and productivity (Raseduzzaman and 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), which represents a major research gap. Field experiments on intercropping should focus on competition for resources (water, nutrients and light), which ultimately determines 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 crop development, negatively affecting the 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 the soil biota, all of which are relevant for soil functions.

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

Although the traditional concept of diversity in cropping systems has been successful for millennia, industrialized farming practices have led to simplified cropping systems. As a consequence, pests and diseases are typically kept under control by the application of agrochemicals, and soil fertility is maintained by elevated fertilizer use, both of which yield side effects for 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), which may require more support from researchers quantifying long-term effects on soil functions as well as the costs and benefits of diversified crop rotations for farmers and society.

Thus far, breeders' efforts have mostly focused on improving aboveground characteristics, whereas phenotyping of root traits and root growth in native soils has received much less attention in the past because of the difficulties involved in such studies. It is known that plant root exudates shape the rhizosphere microbiome and, thereby, also soil structure in a genotype-dependent and inheritable way (e.g., Peiffer et al., 2013). Thus, future breeding activities could also address the selection of 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 (Pérez-Jaramillo et al., 2016). However, this type of diversity will require 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 such as 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 mentioned traits. To support breeding in this regard, fundamental soil and plant research addressing the genetic base of traits, such as the 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 3: Mixture of diverse catch crops (©Deutsche Saatveredelung AG).

Apart from breeding, the general idea of beneficial effects of biodiversity in agroecosystems is based on three pillars: 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 (Section 3.1), intraspecific crop diversification (within-crop diversity), crop rotation, catch cropping and symbiotic chain management. The intensification of cropping cycles by integrating agrobiodiversity and reduction of bare fallow periods are paramount for the optimization of nutrient cycling, erosion control, and efficient land use. 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. However, perennial plants, such as apples, are special cases, with a high degree of specialization for their culture and investments into field facilities for irrigation and hail protection, among others. Here, crop rotations are no longer a viable option for owners of tree nurseries and fruit orchards in centers of production, leading to economic and ecological damages by replant diseases (Mazzola and Manici, 2012; Winkelmann et al., 2019). Research is urgently needed to understand the etiologies and to develop sustainable counteractions to maintain or restore soil health.

One way to improve diversity in crop rotations is the inclusion of catch crops. 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 (Poeplau and Don, 2015). Catch crops have been shown to increase soil quality by improving biological, chemical and physical soil properties, including the organic carbon content, cation exchange capacity, microbial biomass and diversity, aggregate stability, and water use efficiency (Dabney et al., 2001). Most studies, however, have focused on the application of single catch crop species or blends of two species (Tribouillois et al., 2016). Highly diversified catch crops (Figure 3) in blends of various species (5 to 20) with different rooting depths, trophic levels and symbiotic relationships, have emerged as a promising tool to further improve the advantages of catch cropping. However, studies on highly diversified catch crops are very scarce to date. Currently, little is known about 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 based on a synopsis of soil literature specifically assessing the effect of farming practices on soil fertility. They found that soil amendments, cover crops and the use of crop rotation had the highest certainty and effectiveness scores related to beneficial effects on soil.

The management of functional redundancy and functional niching can also (and ideally) be controlled by catch cropping. Although little emphasis has been placed on the management of symbiotic chains related to catch cropping thus far, this factor seems especially rewarding. Mycorrhiza allows for several combinations between certain arbuscular mycorrhizal fungal (AMF) species and plants; thus, the performance of a catch crop is believed to have a certain plasticity due to potentially varying alliances and might thus change between years with different environmental constraints. Since AMF are spore-forming, the genetic reservoir in the soil can increase from rotation to rotation. Most of the abovementioned functions have been reported to be influenced by mycorrhiza in classical papers, such as 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), but they have not been evaluated for their interplay in catch cropping. As mycorrhizal fungi bridge 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, however, this phenomenon remains to be investigated.

In addition, plants are colonized by complex microbial communities, the assembly of which depends, among other factors, on the microbial species that occur in the surrounding environment. The root-soil interface provides a hotspot for microbial activity with multiple niches for microbes, root interior (endorhizosphere), rhizoplane and rhizosphere soil (Reinhold-Hurek et al., 2015), towards the inside of the plant tissue, 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 depend, e.g., on the 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, the root/rhizosphere microbiota influence the soil microbiota. Studies of natural and agricultural systems have shown large effects of plant-soil feedback on plant growth (Mariotte et al., 2018). However, 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 have received little attention in agricultural management strategies to date. 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 that depends especially on farming practices, including the use of crop rotation, is still incomplete.

Here, we identified a knowledge gap, in which research on the impact of diversified catch crop mixtures along with their symbionts on soil functions is highly demanded. Functional traits between species, their interactions with the soil-rhizosphere microbiome and their potential benefits for plant nutrition in cash crops should be investigated. Catch crops have been shown to reveal their full potential for crop yield improvements under low fertilizer treatments, in organic cropping systems, and under reduced soil management (Wittwer et al., 2017). Future studies should, thus, focus on fertilizer reduction and 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 concurrently changing 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 in climate change mitigation and adaptation 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 the soil biota, all of which severely damage soil functions, including the production function (Schjønning et al., 2015b). In addition to the undesirable effects, for instance, of soil compaction, on the soil functions, there are operational costs for remediation and alleviation measures, as well as environmental costs (Chamen et al., 2015; Hamza and Anderson, 2005; Keller et al., 2017).

Figure 4: Harvest of sugar beets with heavy machinery, Germany (©Berthold Ortmeier).

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 and Reeder, 1994; Hamza and 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., 2015a). Modern farm vehicles, such as sugar beet harvesters (Figure 4) 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 gains ground (Keller et al., 2017), further expansion of soil compaction is expected.

Due to such 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. Technological measures that are already available to mitigate soil compaction are reducing tire inflation pressure, increasing the contact area of the tire, and reducing the wheel load (e.g., Chamen et al., 2015). In principle, these developments have the 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 simultaneously increased, or when the machine is used more frequently under unfavorable soil conditions. Smaller and autonomous farming machinery, i.e., agricultural robots, are being developed with the possibility of implementation in the next 15 to 20 years, according to expert interviews (Techen and Helming, 2019).

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 habitats for organisms (Warkentin, 2001). Reduced tillage is also an efficient measure to reduce soil erosion because the soil surface is covered with residues and soil sealing is avoided (Bradford and Huang, 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 the regeneration processes decreases with increasing depth depending on soil and climate conditions (Håkansson 2005). 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; thus, it frequently fails to gain the required re-imbursement 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 exhibit an imbalance with external forces imposed on the 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 and Keller, 2007; Lamandé and Schjønning, 2011). Additionally, the number of wheel passages affects the degree of soil compaction. While the first pass of a farm vehicle contributes to the 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, in addition to soil moisture, on soil structure, the organic matter content and 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 understanding of the main soil compaction causes, processes and consequences, there are many knowledge gaps and requirements in soil compaction research, as listed below (without any ranking of importance).

Many studies have focused on stress-propagation during wheeling and soil compaction effects on soil properties (e.g., Arvidsson and Keller, 2007; Berisso et al., 2013; Schjønning et al., 2015a). Although farmers are aware of the relevance of soil moisture and weather conditions, knowledge about the quantitative effects of soil compaction and soil deformation on soil structure, soil structure dynamics and related soil physical, chemical and biological processes is limited (Vereecken et al., 2016) and requires 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 have shown a decreased yield in compacted areas (e.g. Radford et al., 2007), others showed 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 focuses on soil compaction, despite the numerous environmental issues. Thus, a more systemic view (Vogel et al., 2018; also section 4) on soil and its interrelations with other environmental compartments is needed. For instance, soil erosion and surface runoff also depend on soil compaction (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 subdisciplines 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 are mostly assumed to be static (e.g., 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 the dynamic load input, load transfer and deformation behavior under rolling wheels (e.g. Schjønning et al., 2015a) to acquire a more realistic view of soil compaction processes.

However, the use of large machines is not to be assessed as negative in general. By reducing the wheeling intensity, a higher proportion of the field can remain unaffected by wheeling. However, the wheeled area by the larger (and possibly heavier) machinery may result in a higher degree of soil compaction. An evaluation is necessary whether the larger working width (including heavier machinery but less wheeled area) is better or worse compared to lower working widths with possibly increased 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., Bochtis et al., 2014; Edwards et al., 2017; Hameed et al., 2012). 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 applied at exactly the same time the soil is 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 next. The intra-annual variation of soil moisture, soil mechanical strength and machinery-induced stress inputs are usually not considered in soil compaction assessments on regional to supra-regional scales. Lorenz et al. (2016) provide examples of how trafficability may change during the year. The consideration of dynamic changes in soil properties requires further field analyses and integration in soil compaction modeling.

For subsoils, there is increasing evidence that its properties affect the spatial distribution of, e.g., leaf area indices in the landscape (von Hebel et al., 2014). Additionally, increased 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 (Gaiser et al., 2013; see also below).

Classical soil sampling and soil measurements are very helpful to analyze soil compaction effects, but they are time and labor-consuming. To reduce both time and effort, novel penetrometer devices are under development that simultaneously allow measurements of the soil texture via friction (Schmittmann and Schulze Lammers, 2018). Additionally, a range of geophysical tools are available, such as ground-penetration radar or electric resistance tomography, which may provide indirect measures of the soil water distribution and porosity (e.g., Vereecken et al., 2016).

At the field scale, soil compaction can exhibit huge spatial variability. With site-specific treatment of soil compaction, only parts of the fields need to be plowed, and considerable amounts of fuel can be saved (Kichler et al., 2007). However, mapping of the field variation of soil compaction is a formidable task, which has not been sufficiently solved up to date. Vertical cone penetrometers have been used for a long time in agriculture to detect soil compaction. Efforts have been exerted to design automated cone penetrometers with GPS registration for soil mapping which operate in a stop-and-go mode (Domsch et al., 2006; Drummond et al., 2000). However, due to the high variability of penetration resistance and the requirement to probe within short distances, mapping of a field with vertical penetrometers is not economical (Domsch et al., 2006). Consequently, systems for continuous mapping are favored. There are three main approaches: a) horizontal penetrometers, which measure the horizontal penetration resistance (Andrade- Sánchez et al., 2007); b) draft force sensors and vertical force sensors, which are attached between the tractor and a tillage implement (Hemmat and Adamchuk, 2008; Tsiropoulos et al., 2015); and c) registration of the fuel consumption of the tractor during tillage operation (Boon et al., 2005; Kichler et al., 2007). Hemmat and Adamchuk (2008) provide a thorough review of the penetrometer system and draft force/vertical force sensors. Shamal et al. (2016) describe an integrated system of three sensors for bulk density mapping. The measurement of fuel consumption is an elegant approach that implements the “tractor as a sensor”. However, as with the other approaches, translating fuel consumption into soil compaction and prescription maps is difficult. Until now, none of the approaches for continuous mobile mechanical sensing have been transferred into practice. Although penetration resistance measurements enable the identification of soil compaction patterns, it is limited in regard to analyzing soil functionality (e.g., Kuhwald et al., 2016).

Newer imaging techniques, such 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., Diserens and Battiato, 2013; Keller et al., 2007; Schjønning et al., 2008) and to estimate the potential soil compaction risk (e.g., Rücknagel et al., 2015). Many of the existing soil compaction models consider the entire soil as a homogeneous, isotropic and non-layered medium with uniform stress propagation. 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 the 1D (e.g., Stettler et al., 2014), for 2D (e.g. D'Or and Destain, 2014) and 2,5D (e.g., Keller et al., 2007; Schjønning et al., 2008, 2015a) 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 and Salokhe, 2002) or on single plots during wheeling experiments (e.g., Keller et al., 2014). The transferability of these results to the field or regional scale is limited (e.g., van den Akker and Hoogland, 2011; Keller et al., 2017). As soil properties such as bulk density are not homogeneously distributed in the landscape, effective parameters are needed to allow an upscaling of soil compaction effects from laboratory measurements to the field scale and further to the 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, prevent possible soil compaction. To achieve this aim, Vereecken et al. (2016) called for the development of a simplified semiempirical soil compaction model for the ecosystem-scale. A modeling approach to predict the spatiotemporally varying patterns of soil compaction risk at regional scales has been described by Kuhwald et al. (2018).

Status surveys and Permanent Soil Observation Areas (referred as 'BDF' in Germany), 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 an example, such studies, unfortunately, 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 and Schwark, 2006). Reviews have been published by Brunotte et al. (2008) and Lorenz (2008). An overview of works and surveys on the status of soil compaction in Europe is provided by Vorderbrügge and Brunotte (2011), Houšková and Montanarella (2008), Houšková and van Liedekerke (2008), Le Bas et al. (2006) and Schjønning et al. (2016a). In the future, there is a need for reliable information about the spatial distribution and extent of soil compaction. Therefore, coordinated long-term surveys about the status of soil compaction on arable, grass- and agroforestry land, as well as in fruit orchards and forests are necessary.

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

The mitigation of subsoil compaction requires high energy inputs, e.g., for deep tillage, and thus it is often not sustainable from an economic perspective. In addition, deep tillage includes the risk of diluting beneficial topsoil properties with subsoil material. Thus, novel ideas are aimed 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 later utilize these biopores for their own vertical movement into the soil, stabilizing them with their faeces (Athmann et al., 2017), while simultaneously providing surfaces with an elevated nutrient supply and turnover (Barej et al., 2014; Bauke et al., 2017; Han et al., 2017). Thus, future biological efforts might aim 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 matter, 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 or other xenobiotics 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 identify opportunities and threats and to contribute to the development of changed management practices. These include changes in organic inputs (including carbon, plastics, pharmaceuticals, and others) and recycled nutrients, biotic inoculation, irrigation (including wastewater), and changes in the precision of fertilizer and pesticide (including timing and amount) application. The addition of lignocellulosic crops to cropping systems (e.g., agroforestry) and changes in crop rotations both also change soil organic matter dynamics, which are discussed in sections 3.1 and 3.2, respectively.

Soil organic matter plays a key role for in soil fertility by improving soil physicochemical and biological properties (Swift, 2001). However, intensive agricultural practices associated with a 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 the specialization of farms have resulted in a dramatic decrease in the use of farmyard manures (Maltas et al., 2018) and a significantly decrease in 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 the SOC decreases in agricultural soils (Wiesmeier et al., 2015), although in many regions, legacy effects from former land conversion also continue to contribute to current SOC losses (e.g., Sanderman et al., 2017; Steinmann et al., 2016). 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., Thrän et al., 2016; Weiser et al., 2014). This would likely further decrease the amount of organic inputs 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 a 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) have estimated that up to 90% of the total mitigation potential in the agricultural sector could be derived from SOC sequestration, with approximately 10% from the reduction of non-CO_2 greenhouse gases, such as nitrous oxide and methane. 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 with impermeable layers, such as concrete and asphalt. Furthermore, a 4 per 1000 increase suggests a curve pattern that is far from reality because C sequestration rates either show a time lag, i.e., sigmoidal curve shape, or follow a saturation pattern, with less potential C uptake close to C saturation (e.g., Hassink, 1997; Post and Kwon, 2000; Preger et al., 2010; Six et al., 2002). However, 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 (de Vries et al., 2018; Duarte-Guardia et al., 2018; Minasny et al., 2017). This is of particular importance because as the carbon input by plants, particularly the belowground input in form of roots and rhizodeposition, is largely unknown (Kuzyakov and Domanski, 2000; Pausch and Kuzyakov, 2018). This emphasizes the need for precise quantification of the 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, the application of organic soil amendments with high carbon (HCA) content, such as straw, sawdust and biochar, have received growing attention in recent years as a means to increase SOC content and improve soil functions. 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 and Montemurro, 2010). The combined application of HCA, mainly in the form of straw, and mineral N fertilizer, has been shown 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 not be always the best parameter for prediction of the effects of the HCA on soil processes, especially nitrogen dynamics, but more the soil properties and 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 that participate in (bio)chemical reactions, in 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 has been found to play a central role in regulating soil nitrogen dynamics and, especially, the formation of N_2O, a potent greenhouse gas (Feng and Zhu, 2017; Lan et al., 2017). The effects of stoichiometric relationships, also including the 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 on this topic has to deal with 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, suggests that soil application of biochar may be a promising strategy for both long-term carbon sequestration and soil improvement (Lehmann and 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 avoid degradation in the soil (Bamminger et al., 2014; Kuzyakov et al., 2014). 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 under field conditions. Agronomic yield effects of biochar have been reviewed at the European level for pot experiments (Sakrabani et al., 2017) and field trials (Verheijen et al., 2017). Most experience is available from biochar experiments conducted in tropical environments. Although few studies have been published on experiments with biochar in temperate soils with clear positive yield effects (Atkinson et al., 2010; Bell and Worrall, 2011), others have reported negative findings (Borchard et al., 2014; Jeffery et al., 2011). Clearly, more scientific studies are required to assess the agronomic potential in temperate soils. The innovative approach of biochar “activation” to improve the yield response has triggered research on various biotechnologies to produce modified biochar (Glaser and Birk, 2012). One option is a form of co-composting, delivering a nutrient-enriched biochar (e.g., Prost et al., 2013). However, to which extent such activated biochars lose their stability against microbial degradation has not yet been clarified.

The response of soil organic matter 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 (Barthod et al., 2018; Diacono and Montemurro, 2010). 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 also imposes new chemical risks by introducing novel compounds into the ecosystem, such as plastics (Bläsing and Amelung, 2018), antibiotics (Xie et al., 2018), disinfectants (Mulder et al., 2018), and other priority pollutants. These include ingredients for animal production as well as products for human use, such as hormones and other human pharmaceuticals, which are 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. Additionally, nothing is known on possible interactions between chemical soil stresses induced by such pollutants and other, e.g., physical or biological stresses. Syn- and antagonistic effects may enforce selected risks, but they can also increase soil resistance and resilience. For a novel discussion of such interactions, the concept of xenoresilience in soils has been suggested by Schaeffer et al. (2016), although it warrants experimental verification.

Contamination of soils with plastic is gaining increasing attention due to the persistent nature of the materials. Mulching of soils with plastic foil is an efficient measure to increase the soil temperature while retaining moisture and suppressing 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 is currently covered with plastic foil (Scarascia-Mugnozza et al., 2012). 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 parts of sewage sludge and compost. Nizzetto et al. (2016) have assumed that in Europe, for instance, sewage sludge application alone adds between 63 000 and 430 000 tons of microplastics to the soil annually. Data for compost are scarcer, but it could comprise an annual input of 0.02 to 6 kg plastic ha^{-1}, particularly after the application of compost from municipal biological waste (Bläsing and Amelung, 2018). Investigations on the ecotoxicity of plastics in field soil are still in the fledgling stages and need to be advanced.

Figure 5: Planted vegetable field with plastic mulch foil in Germany. Source: Florian Gerlach (Nawaro) [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons.]

Additionally, compounds such as pharmaceutical and disinfection products reach the soil, which have been specifically designed to kill or at least inhibit microbial growth (see reviews by Jechalke et al., 2014; Mulder et al., 2018). These compounds enhance the formation and selection of resistance genes that are already present in the animal, and later also in the soil, thereby potentially contributing to the increasing emergence of multiresistant human pathogens (Forsberg et al., 2012). In soil, the presence of labile C sources in particular, for instance, in liquid manure, fosters microbial growth and thereby enhances also the 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, such as perfluorooctanoic and perfluorooctanesulfonic acid, may have specific detrimental effects on soil faunal members such as earthworms (Zareitalabad et al., 2013), though their input in the 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 the spread of diseases, which has a higher priority than soil conservation.

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 for fertilizer production, and they have also spurred European regulations and policy discussions 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). 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 the 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., 2019). However, in principle, all P-recycling products need to be tested for agronomic effectiveness in long-term experiments, which has not yet been done, and the legal regulations for their application are far behind the scientific and technical developments in P recycling.

Research has shown that the inoculation of soils and seeds with mutualists of crops and antagonists of pests can lead to better yields and reduce the 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 for more than 150 years (for reviews see Mahmood et al., 2016; Triplett and Sadowsky, 1992). However, the success of the microbial inocula to soil has been discussed controversially in the literature, as the results were, in many cases, strongly dependent on site-specific conditions such as 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, the 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 have greater focus on the development of approaches for sustainable inoculation of plant-beneficial microbes in soils using existing bacterial or fungal strains, rather than the isolation of 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 endowed the inoculum with an artificial (temporal) niche in the soil after application and protected the introduced microbes from grazing and competition with the autochthone microflora of soils (for a review see Malusá et al., 2012). These techniques must be further developed, including the use of waste materials to ensure the most effective use of natural resources in an environmentally friendly manner. Another possibility is the use of nematodes as carriers for the 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, as long as 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, in practice, a great research challenge is encountered, as both nematodes and bacteria need to be cultivated and introduced into soils.

Even if most inoculations have not been sustainable, it must be considered that any introduction of living microorganisms into soils bears the risk that those microbes can develop their own dynamics in soils. 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 the pesticide application. Although some research on the effects on non-targeted organisms is still needed, negative effects are generally much less expected than from chemical pesticides (Kergunteuil et al., 2016). However, technical and economic obstacles remain for the wide application of antagonists against soil-borne pests, and research, including industrial research, currently seems to be the decisive driver towards the inoculation of soils with natural enemies of pests (ibid.).

The concern about the detrimental effects of microbes in soil is especially justified with respect to the use of wastewater for irrigation purposes, which has been banned in many countries in recent decades for health reasons, but which has recently been reconsidered as an important irrigation source in areas with a water scarcity. This phenomenon may also become relevant in Germany in view of the expected increase in irrigation demand due to climate change in Germany (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 it 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 to antibiotics, may cause problems both for human and environmental health. Although initial assessments and strategies for wastewater irrigation have been defined (e.g., EC, 2018; Seis et al., 2016), which include the use of pretreated wastewater in the future, further research on the activity and fate of the introduced, potentially harmful microbes, is mandatory.

There is a strong trend towards the development of technologies for higher precision in applying fertilizers and pesticides. A reduction of application rates for pesticides in particular, and higher N-efficiencies for fertilizers are expected. 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 into some parts of the fields, while other parts receive excessive inputs, which wastes resources, degrades the soil and pollutes the environment (Whelan and McBratney, 2000). This problem can be solved by site-specific soil management in precision agriculture (Gebbers and Adamchuk, 2010). Although 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), mainly because 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 has shown that the sampling density is the most relevant factor for the precise application of inputs (Gebbers and de Bruin, 2010; Schirrmann et al., 2011). For example, sampling intervals of approximately 18 m are required to capture spatial differences in variable quaternary sediment soils. However, bulk sampling over a 1-ha grid is acceptable to ambitious farmers, 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 spatiotemporal resolution of soil monitoring (Whelan and McBratney, 2000), but they 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 that research results on soil nutrient dynamics have been only incompletely adopted yet in practice (Wallor et al., 2017). For example, available knowledge on subsoil processes is not taken into account in 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 in a timely and cost-effective manner at high spatial and temporal resolution; b) evaluation of these new soil data by the adaptation 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 socioeconomics 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 have more accurate, soil pH-dependent equations for estimating the content of plant-available P 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 the 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 the 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 for reducing the overall P fertilizer applications along with a wide range of other approaches to reduce the P input and, thereby, the environmental impacts of excess P in soil (Leinweber et al., 2018).

4. Cross-cutting research challenges

Complementary to the specific soil research challenges, as outlined in chapter 3, there is a need for cross-cutting research activities to operationalize soil knowledge for decision-making in practice and policy, which includes an integrated approach of natural and socioeconomic sciences to understand the conditions and constraints of implementing sustainable soil management practices. Soil process knowledge needs to be synthesized into metrics 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 the adoption 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 socioeconomic conditions. Basic support for this is provided by sophisticated data repositories that permit the reuse and recombination of soil research data, particularly those from long-term experiments. These elements are briefly outlined below.

4.1 Data management

Scientific databases have been recognized as a crucial part of the science system 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 the 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 (Hodson et al., 2018; Wilkinson et al., 2016). 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 methodological development (Hoffmann et al., 2018; Svoboda et al., 2018).

Methodological 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 3.3). Technological advances and the increasing digitization in agriculture and, thus, 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 also 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, the value of the data, privacy and security. Agricultural technology providers, which operate their own cloud platforms, play an important role in this context. On the one hand, there is the development towards closed, proprietary systems, and on the other hand, towards more open systems, which are based on open standards and interfaces (Kamilaris et al., 2017).

Soil and agricultural sciences research makes use of a wide variety of data, e.g., laboratory data, logger data, field observations, landscape monitoring, sequence data, phenotype data, spectrophotometer data, sensor data, and images. New data sources, such as 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, for which some trials have been carried out for more than 100 years, deliver important information for answering current and future questions on soil use, soil productivity and, not least, 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; Grosse and Hierold, 2017; Perryman et al., 2018).

The exploitation of modern data capture, transfer and analysis technologies can improve soil management practices and permit more sustainable farming methods (Nathanail et al., 2018).

4.2 Modeling

As an important prerequisite for including soil functions in sustainability assessment and science-based decision support, the impact of soil management on soil functions must be quantified. It is a widely shared conception that soil functions are systemic properties emerging from a myriad of complex process interactions 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 need to be predicted based on a 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 the simultaneous modeling of various soil functions in response to external perturbations caused 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 by 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 modeling these "soil functional characteristics" (Vogel et al., 2018) is a formidable challenge for future research.

For example, the extent to which the microbial diversity in soil must be considered to model the nutrient use efficiency of plants or the turnover of organic matter remains an open question. There is some evidence that the functional redundancy of soil organisms may allow for the simplification of diversity and description of 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. Modeling the effects of crops, crop rotations and catch crops on soil structure, especially in the subsoil (as discussed in section 3.2), requires some knowledge about the capacity of plant roots for structure formation or their tendency to reuse existing pores. The same is also required when modeling the recovery of soils after compaction (as discussed in section 3.3), which must also 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 they have not yet been included into commonly used models.

Asking from a top-down perspective which models are required to evaluate measures taken towards achieving sustainability goals, makes the need for a systemic model approach obvious. For example, the reduction of pesticides does not just protect useful insects, but 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 these features depend on the local site conditions in terms of the soil type and climate. Similar scenarios can be devised for other sustainability targets, such as the '4 per 1000' initiative as described in section 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 modeling. To establish 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 experiments.

4.3 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 (SDG, UN General Assembly, 2015) through their contribution to food provision (SDG2), climate change mitigation via carbon sequestration (SDG 13), support of 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 across 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 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 and nutrients (Struik 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 they 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 the resource use efficiency. However, the associated impacts of introducing waste material (plastics), organic pollutants (antibiotics) and (micro)organisms into the soil system on the environment and human health are not well understood. Risk assessments must be established that build upon the precautionary principle and that can inform legislation regarding the utilization of recycled and newly developed substances that are introduced 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/); however, 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 the farm level. While soil is a private good, many 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 specifically for the other ecosystem and climate services, which the soil provides, except to some degree for the green direct payments and agri-environmental measures of the Common Agricultural Policy of the European Union. 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 instruments. However, such payments require the (monetary) valuation of soil ecosystem services, an approach that is not yet well established and for which data are barely available (Jónsson et al., 2017). An emerging field of research comprises the governance implications of the nonexisting attribution of property rights to specific soil provided ecosystem services (Bartkowski et al., 2018).

Many soil-improving practices only pay off in the long term, and such long-term benefits are difficult to monetize and account for in cost-benefit analyses. The socioeconomic awareness of practices, such as subsoil loosening, is not yet well established (Frelih-Larsen et al., 2018). Here, property rights are an important factor because farmers may tend to pay less attention to long-term 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 are however rare (Daedlow et al., 2018). Public policy for sustainable soil management must incentivize particularly those ecological intensification practices that reinforce the inherent capacity of soils to produce biomass (Tittonell, 2014), without endangering the provision of other soil services. However, the 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 and 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), which 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). Additionally, investigating and unleashing the potential of informal governance instruments (e.g., Price and Leviston, 2014) are required for more effective governance.

4.4 Stakeholder interaction

New knowledge and the adaption of decision-making to address sustainability challenges requires the interaction with actors from outside academia (Lang et al., 2012) as well as 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 the implementation of land-use practices (Rounsevell et al., 2012). To prevent disillusionment and drawbacks, effective stakeholder interaction must carefully define the objective (information, consultation, knowledge co-production and empowerment – Enengel et al., 2012) as well as the 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. Soil scientists need to take stakeholder engagement serious early on and in a systematic way so that the process enables empowerment, equity, trust and learning. Recently identified strategic land use and soil management research demands (Nathanail et al., 2018) emphasize the role of stakeholders 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 new scientific questions in soil science as well as in cross-cutting research. We have assessed research challenges along four categories of soil management and for cross-cutting topics for Germany as an example of countries with a 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 are also driven directly by research itself by uncovering benefits and management details. Research needs are focused on nutrient use and retention efficiencies and on water consumption at the field scale in agroforestry systems compared to conventional agriculture and how to optimize them through management. Additionally, the effectiveness of agroforestry in reducing 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 have been identified especially in the area of root architecture and functions, as well as an 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, a better understanding of the 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 the actual compaction risk and the 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 reveal to 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, are 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 field experiments, not just for carbon sequestration but mainly to improve soil organic matter management. The effects of stoichiometric (C:N:P) relationships on soil nutrient dynamics and nutrient use efficiency, as well as the long-term agronomic effectiveness of P-recycling products and ecotoxicity of plastics and pharmaceuticals in soil gain relevance in the context of resource scarcity and circular economy strategies, which may lead to an increased use of organic waste or associated products. The advancement of biotic inoculation methods towards sustainable field applications is one research challenge 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 the sustainable intensification of agricultural production (Garnett et al., 2013). For soils, this means that the production function of soils must 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 the results of this study into the formulation of key research challenges, which we assessed in terms of their relevance for the five soil functions (Figure 6) and for soil threats describing key soil degradation processes (Figure 7). The perspective of soil threats widens the foresight perspective in the direction of risks associated with soil management. Among the soil threats defined in Thematic Strategy for Soil Protection of the European Commission (EC, 2006), the following are considered 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 the field scale. We have also excluded salinization because this is not considered a soil threat under the climatic and soil conditions in Germany (Tsanis et al., 2016).

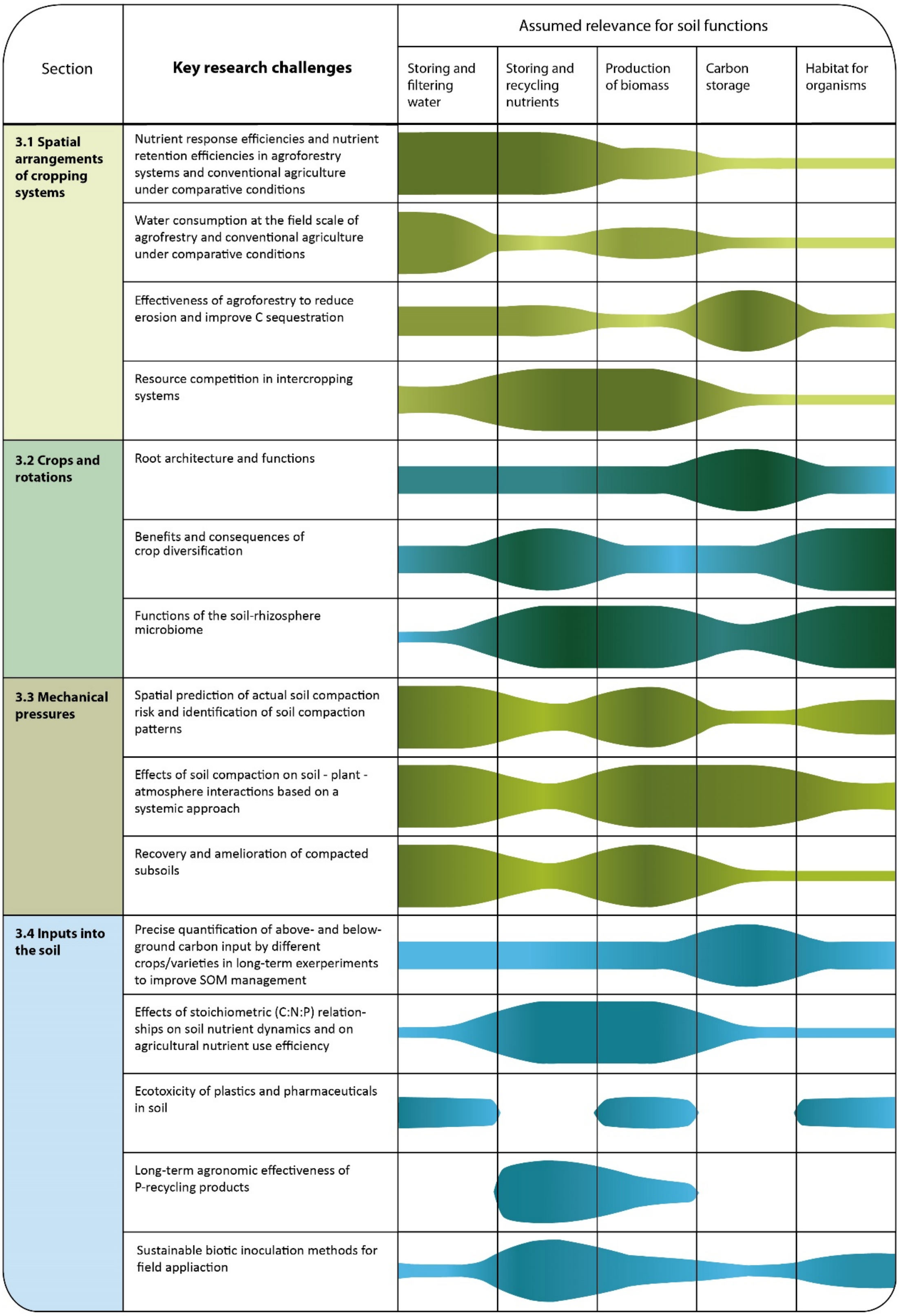

Figure 6: Key research challenges and their assumed relevance for soil functions.

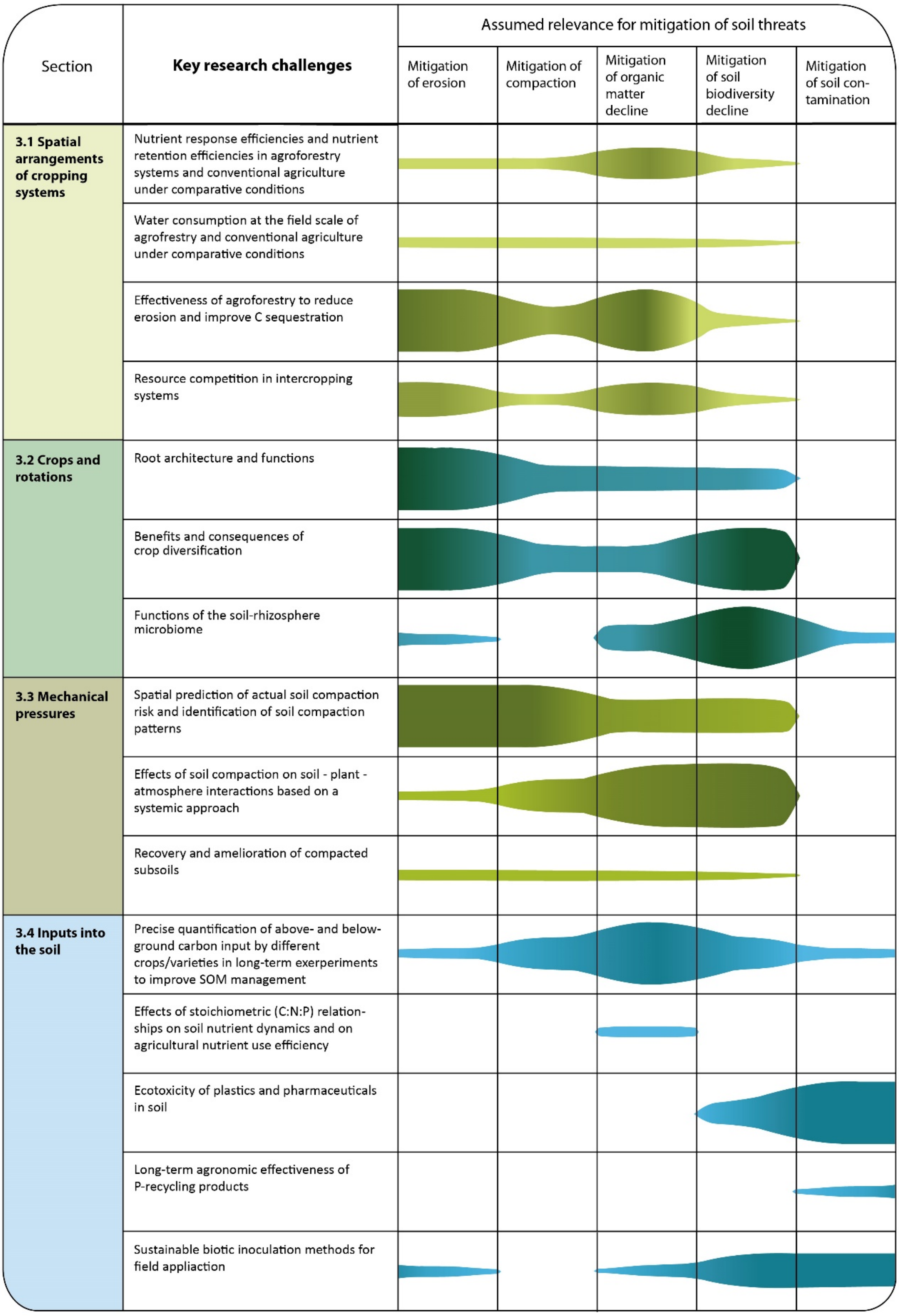

Figure 7: Key research challenges and their assumed relevance for soil threats.

Except for one of the identified key research challenges, all of them have been identified as being relevant for all five soil functions (Figure 6). 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. Nevertheless, most key research challenges have been assessed to be more relevant for the three soil functions “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 the ones 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 7). 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.

Knowledge gaps and soil research challenges associated with the functioning of new management practices involve multiple spatial scales, ranging from the microbiome up to the landscape level (Ludwig et al., 2018). At the scale of the microbiome, the complex microbial communities at the root-soil interface determine nutrient uptake and pest regulation. At the plant scale, the dynamic root architecture determines the best use of space and time with regards to access to water and nutrients. At the field scale, it is the spatial and temporal pattern of crops competing for water, energy, and nutrients aboveground and in the soil. In addition, patterns of field traffic affect the mechanical pressure on the soil. At the landscape scale, the spatial arrangement of the crops, including tree crops, affect the humidity and heat fluxes, the spread of diseases, the interplay between pests and antagonists as well as lateral processes such as wind and water erosion and water and nutrient flow into adjacent ecosystems. Such mechanisms are not only relevant for crop growth, but they also lead to offsite impacts that affect ecosystem services beyond the agricultural systems. The landscape scale is therefore paramount for assessing the sustainability impacts of the interactions between cropping systems and soil processes (Helming and Pérez-Soba, 2011) and for assessing the contributions of soil functions to the full range of ecosystem services (Hatfield et al., 2017). The interactions between such processes at different scales are not yet well understood and require sophisticated methods of up- and downscaling (Ewert et al., 2011). This is a key challenge in developing the evidence base of how soil management can better activate natural pest and disease management functions, foster internal nutrient cycles, support the indigenous soil food web and improve the utilization of the soil pore volume for access to water and nutrients.

While the specific soil research topics are crucial for advancing sustainable soil management and sustainable intensification, the cross-cutting research challenges (Figure 8) address the need for synthesis, generalization and upscaling of research results to make the knowledge accessible for a wide range of decision support. The availability of data is decisive for fulfilling such tasks and 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. Modern data capture, transfer and analysis technologies also lead to challenges in exploiting research data to improve soil management practices towards sustainability. Furthermore, since soil functions are integral properties emerging from a multitude of complex process interactions, complex soil models that are embedded in a systemic approach are needed to address the impact of soil management on soil functions. Research challenges are also encountered in comprehensive sustainability assessments that place 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 the societal relevance of soil functions, but they need supplementation, for instance, in the direction of assessing impacts of soil management on human health. The assessment, economics and governance of sustainable soil management require an interdisciplinary approach that involves socioeconomic and natural science expertise as well as stakeholder interactions. Systematic stakeholder engagement is a crucial challenge along the whole chain of research to enable sustainable soil management.

Section 4: Key cross-cutting research challenges
The management of the diverse and heterogeneous soil and agricultural research data, including data from long-term field experiments, requires standardization to achieve interoperability.
Soil functions are integral properties emerging from a multitude of complex process interactions. We need a systemic modelling approach to address the impact of soil management on soil functions.
The relevance of soil functions for societal challenges can be addressed, e.g., with the concepts of ecosystem services and of resource use efficiency.
The assessment and governance of sustainable soil management requires an interdisciplinary approach involving socio-economic and natural science expertise.
Early on systematic stakeholder engagement is crucial to enable sustainable soil management.

Figure 8: Key cross-cutting research challenges.

6. Conclusions

Agricultural soil management is quite diverse, develops over time and is continuously adapted, driven by socioeconomic, biophysical and technological factors. Soil research must react on these developments by identifying research challenges and tackling these challenges via systemic and interdisciplinary studies. In addition to short-term research projects, advanced knowledge derived from long-term field experiments is crucial to finally generate applied recommendations and decision support for optimized soil management as well as for societal and political stakeholders. In this review, 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, with a focus on the next five to 10 years. Still, some important aspects could not be covered, such as the functional role of soil fauna and how it is affected by soil management. Additionally, 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 while maintaining or improving the other functions, such as the habitat for organisms.

Thus, this initial 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 optimal implementation of practices and technologies to maintain soil functions and realize a sustainable intensification.

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