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RESEARCH ARTICLE

Sustainable soil management measures: a synthesis of stakeholder recommendations

Veronika Strauss[1,2] · Carsten Paul[1] · Cenk Dönmez[1,3] · Michael Löbmann[1] · Katharina Helming[1,4]

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Abstract

Soil degradation threatens agricultural production and soil multifunctionality. Efforts for private and public governance are increasingly emerging to leverage sustainable soil management. They require consensus across science, policy, and practice about what sustainable soil management entails. Such agreement does not yet exist to a sufficient extent in agronomic terms; what is lacking is a concise list of soil management measures that enjoy broad support among all stakeholders, and evidence on the question what hampers their implementation by farmers. We therefore screened stakeholder documents from public governance institutions, nongovernmental organizations, the agricultural industry, and conventional and organic farmer associations for recommendations related to agricultural soil management in Germany. Out of 46 recommended measures in total, we compiled a shortlist of the seven most consensual ones: (1) structural landscape elements, (2) organic fertilization, (3) diversified crop rotation, (4) permanent soil cover, (5) conservation tillage, (6) reduced soil loads, and (7) optimized timing of wheeling. Together, these measures support all agricultural soil functions, and address all major soil threats except soil contamination. Implementation barriers were identified with the aid of an online survey among farmers ($n = 78$). Results showed that a vast majority of farmers ($> 80\%$) approved of all measures. Barriers were mostly considered to be economic and in some cases technological, while missing knowledge or other factors were less relevant. Barriers were stronger for those measures that cannot be implemented in isolation, but require a systemic diversification of the production system. This is especially the case for measures that are simultaneously beneficial to many soil functions (measures 2, 3, and 4). Results confirm the need for a diversification of the agricultural system in order to meet challenges of food security and climate change. The shortlist presents the first integrative compilation of sustainable soil management measures supporting the design of effective public or private governance.

Keywords Agriculture in transition · Diversification in agriculture · Soil functions · Soil health · Sustainable soil management · Stakeholder recommendations

1 Introduction

Agricultural soils are multifunctional. Beyond food production, they filter and store water, store and recycle nutrients, sequester carbon, and provide habitat for biological activity (Schulte et al. 2014). These functions play a crucial role in the resilience of agricultural production systems and agricultural landscape ecosystems. However, the ability of soils to perform these functions is threatened by degradation processes such as erosion, compaction, biodiversity decline, organic matter decline, or contamination (Glæsner et al. 2014). While the intensification of agriculture has strongly increased productivity, a concurrent rise in soil threats impairs the other soil functions (Techen and Helming 2017; Virto et al. 2015). Since soil

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✉ Veronika Strauss
veronika.strauss@zalf.de

[1] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany

[2] Institute of Physical Geography and Landscape Ecology, Leibniz University Hannover, Schneiderberg 50, 30167 Hannover, Germany

[3] Landscape Architecture Department, Remote Sensing and GIS Lab, Cukurova University, 01330 Adana, Turkey

[4] Faculty of Landscape Management and Nature Conservation, University for Sustainable Development (HNEE), Schicklerstr. 5, 16225 Eberswalde, Germany

fertility depends on the interplay of all functions, this also threatens long-term food security (Kibblewhite et al. 2008; Wagg et al. 2014). Historically, soil degradation resulting from poor soil management has led to the collapse of civilizations (Olson 1981; Snyder 2020). A sustainable management of agricultural soils that preserves or improves soil functions is therefore a pressing challenge, especially in light of a growing world population and climate change (Lal 2009).

There is increasing awareness among stakeholders of the importance of sustainable soil management. The United Nations (UN) declared 2015 as the International Year of Soils, researchers and institutional authorities highlight the importance of soils for the attainment of the UN's Sustainable Development Goals (EEA 2019; Helming et al. 2018; Keesstra et al. 2016), and recent popular documentaries raise public awareness about the need for soil protection (Tickell and Tickell 2020; Uhlig 2019).

However, at the European Union (EU) level, a legal framework specifically addressing soil protection is lacking (Virto et al. 2015). Although multiple EU regulations, such as the Common Agricultural Policy (CAP), the nitrates directive, the water framework directive, or the habitats directive address soil-related aspects, they do not specifically address the functioning of soils and do not account for the soil system in a holistic approach (Frelih-Larsen et al. 2017). Consequently, legislation pertaining to soil protection is inconsistent in the EU and insufficient for ensuring adequate protection of soils (Glæsner et al. 2014). By the end of 2021, the European Commission published a new Soil Strategy after a failed attempt toward a European Soil Framework Directive in 2014 (SIEUSOIL 2020). The new strategy foresees a soil health law by 2023. This is urgent, especially in view of the transnational magnitude and entanglement of challenges, such as climate change mitigation and adaptation or growing food demand, which threaten the achievement of the Sustainable Development Goals by 2030 (Ronchi et al. 2019; Ginzky et al. 2018).

Even in European countries where a national legal framework for soil protection has been in force for many years, such as in Germany, sufficient soil protection is not guaranteed. The German Soil Protection Act only partially prescribes preventive action, and the principles of good agricultural practices stated in the Act are considered too vague to be effective (Gunreben 2005; Prager et al. 2011; Rothstein et al. 2014). Consequently, soil degradation continues to be a serious problem in Germany and is expected to increase significantly by 2050 (Routschek et al. 2014; Wunder & Bodle 2019). Many stakeholders have become aware of this problem, and many recommendations for soil health-improving management measures in arable systems in Germany and Europe have been published (Fig. 1). They differ in terms of purpose, cost, systemic integration, and transformational requirements. They address different soil threats and soil functions, and their suitability varies regarding geophysical setting, soil properties, and farming system. However, there is still no consensus on what exactly sustainable soil management entails, and the multitude of different recommendations makes it difficult to see the forest for the trees. This hampers the adoption of soil governance measures, so that soil conservation management going beyond the legal requirements currently depends primarily on voluntary actions by farmers (Altobelli et al. 2020; FAO and ITPS 2015; Juerges and Hansjürgens 2018).

While agricultural soils are usually private property and their specific management is determined by farmers, management impacts on soil functions also affect public goods such as biodiversity, water regulation, and climate change mitigation (Powlson et al. 2011). Thus, there is a legitimate public interest in establishing mechanisms of public and private governance, such as regulations, subsidies, certification, and land-renting contracts, that promote sustainable soil management practices. To obtain a high degree of acceptance, which is particularly important in private governance, such mechanisms need to build on a consensus around sustainable soil management measures, which includes the

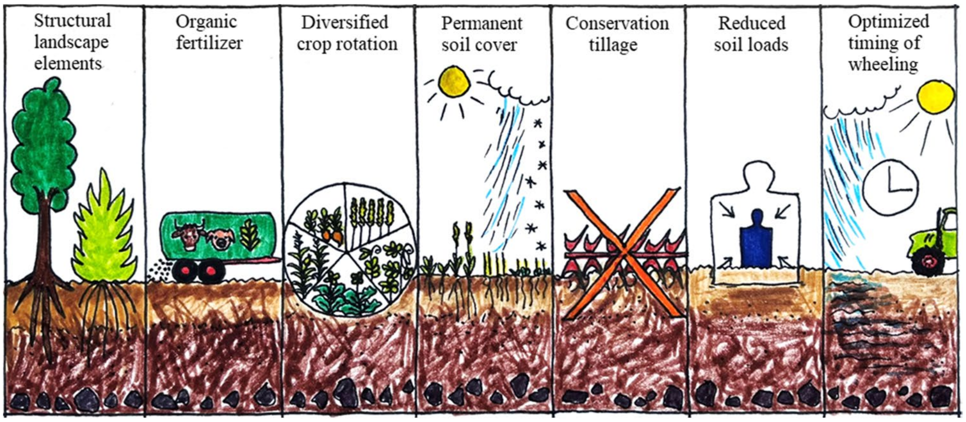


Fig. 1 Soil-improving management measures based on stakeholder recommendations: implementation of structural landscape elements, use of organic fertilizer, diversified crop rotations, permanent soil cover, conservation tillage, reduced soil loads, and optimized timing of wheeling. Picture: Veronika Strauss.

perspectives and concerns of different stakeholder groups (Horschig et al. 2020).

Among the stakeholders, farmers are of central importance, as they are responsible for implementing measures and are directly affected by regulations pertaining to soil management. Although they have a vested interest in managing their soils sustainably, diverse obstacles and drivers for choosing unsustainable management options exist (European Commission 2006). Identifying such obstacles is important for designing governance mechanisms that efficiently incentivize sustainable soil management. Other relevant stakeholder groups are policy makers and public institutions, the agriculture and food industry, and environmental and social nongovernmental organizations (NGOs). To our knowledge, no work has yet been published that analyzes the views of these stakeholder groups toward agricultural measures required for sustainable soil management in a comprehensive way. To contribute to addressing this research gap, our objectives are to:

i. give an overview of the recommendations for sustainable agricultural soil management from different stakeholder groups (longlist),
ii. derive a shortlist of sustainable agricultural soil management measures that meet widespread agreement across all stakeholder groups,
iii. analyze which soil threats and soil functions are affected by these management measures and identify possible gaps, and
iv. analyze farmer perspectives on these measures and identify barriers to their implementation, including possible requirements for systemic change.

The results of our study provide a basis for designing public and private governance mechanisms. We use Germany as an example for a country in the temperate climate zone with highly industrialized agriculture and low yield gaps. We combine an analysis of stakeholder documents with a farmer survey.

2 Materials and methods

2.1 Stakeholder document analysis

2.1.1 Selection of stakeholders

A screening of stakeholders relevant to the German agricultural sector was performed, focusing on stakeholders active at the national or federal state level but also including relevant European and international institutions. Stakeholders were identified using a keyword-based Google search for documents addressing soil management, soil threats, or soil functions, and followed by a snowball sampling method (i.e., identification of one stakeholder could offer the connection to further stakeholders; cf. Atkinson and Flint 2004). All stakeholders were assigned to one of the following categories:

- Public governance and institutions (GOV): ministries, environmental protection agencies, governmental advisory councils; institutions of the European Union and the United Nations;
- Non-governmental organizations (NGO): interest groups with a focus on the environment, social issues, sustainability, or agricultural soils;
- Agricultural industry (IND): companies and industry associations from the seeding, fertilizer, pesticide, and agricultural technology sectors;
- Conventional farming associations (CONV): groups, networks, and associations of conventional farmers in Germany;
- Organic farming associations (ORG): groups, networks, associations of organic farmers in Germany, and organic food labels.

We differentiated between conventional and organic farming associations due to different requirements and limitations applying to both farming systems (Crittenden et al. 2015). For GOV, well-known stakeholders such as international institutions and agricultural and environmental ministries of the German federal states were added. For the other categories, additional stakeholders were identified by searching for the German equivalents of the keywords "NGO" + "environment," "agriculture," or "arable" (NGO); for "agric*" + "seeding," "pesticide," "fertilizer," or "agricultural machinery" (IND); and for "agricultural association" or "farmers union" ± "organic" (CONV, ORG).

2.1.2 Selection of documents

Websites of the identified stakeholders were searched for soil-related documents using the keywords "soil," "soil protection," or the German equivalents. The following four criteria had to be met for a document to be selected:

1. Clear link to agricultural soil management in Germany, or valid globally.
2. Addresses specific management options directly applicable by farmers. Only listing desired outcomes, such as "avoid erosion" was not considered sufficient.
3. Applicable to arable cropping.
4. Specifically addresses soil protection, soil health improvement or sustainable soil management.

2.1.3 Analysis of documents

A full-text analysis was performed for all selected documents. For assessing the agricultural measures addressed, we developed an analytical framework (Fig. 2). The categorization of agricultural soil management measures was based on Techen and Helming (2017). However, we added "farming system" as a fifth main category and slightly modified the subcategories. Similar measures were combined under a common name. For example, "use of manure" and "use of compost" were recorded as "organic fertilizer." All measures were assigned to a subcategory, and linkages between the measures and soil threats or soil functions described in the documents were recorded.

For each measure, we counted the total number of documents addressing it, as well as the number of documents per stakeholder group. Documents issued by multiple stakeholder groups were counted for the group with the largest number of contributing authors. There was one tie where a document had been issued by one stakeholder each from NGO and CONV. We assigned the document to CONV because this stakeholder group is closer to implementing the measures.

The overall share of documents recommending a measure reflects the agreement among the stakeholders. We created a shortlist of measures that were recommended by at least $\frac{1}{3}$ of all stakeholder documents. This share also marks the threshold above which each measure was recommended by at least one stakeholder from each group.

2.2 Farmer survey

We conducted an online survey with German farmers using the open source application LimeSurvey® (version 4.3.15, build 200907, LimeSurvey GmbH, Hamburg, Germany). Although the survey was performed in German language, we refer here to English translations. In June/July 2021, an email with the link to the survey was sent to 16 major German agricultural organizations and 62 local farmer associations across all federal states, with a request to forward it to their members. All complete answers submitted by August 9, 2021, were included in the analysis ($n = 78$).

For all measures on the shortlist, we asked farmers the following questions:

- Is the measure reasonable?
- What is the most important challenge to implementation? The responses to choose from included technology, economic constraints, lack of knowledge, and other (with a comment option).

If the comments provided with the option "other" specified technical/economic/knowledge-related barriers, then the answer was assigned to the respective category. All answer fields were mandatory (except for an open comment field at the very end of the survey). However, there was also the option to answer "I don't know/no answer."

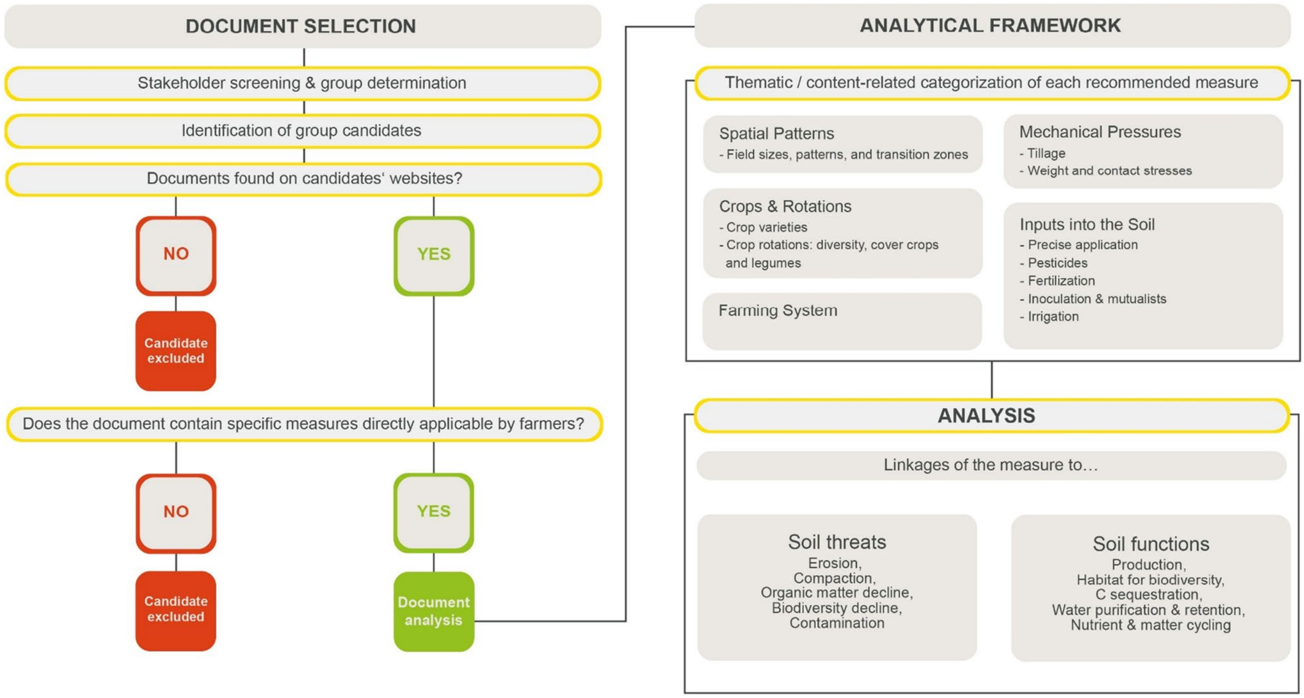


Fig. 2 Framework for document selection and analysis. The approach for categorizing of the measures was adopted from Techen and Helming (2017). Soil threats: Glæsner et al. (2014); soil functions: Schulte et al. (2014).

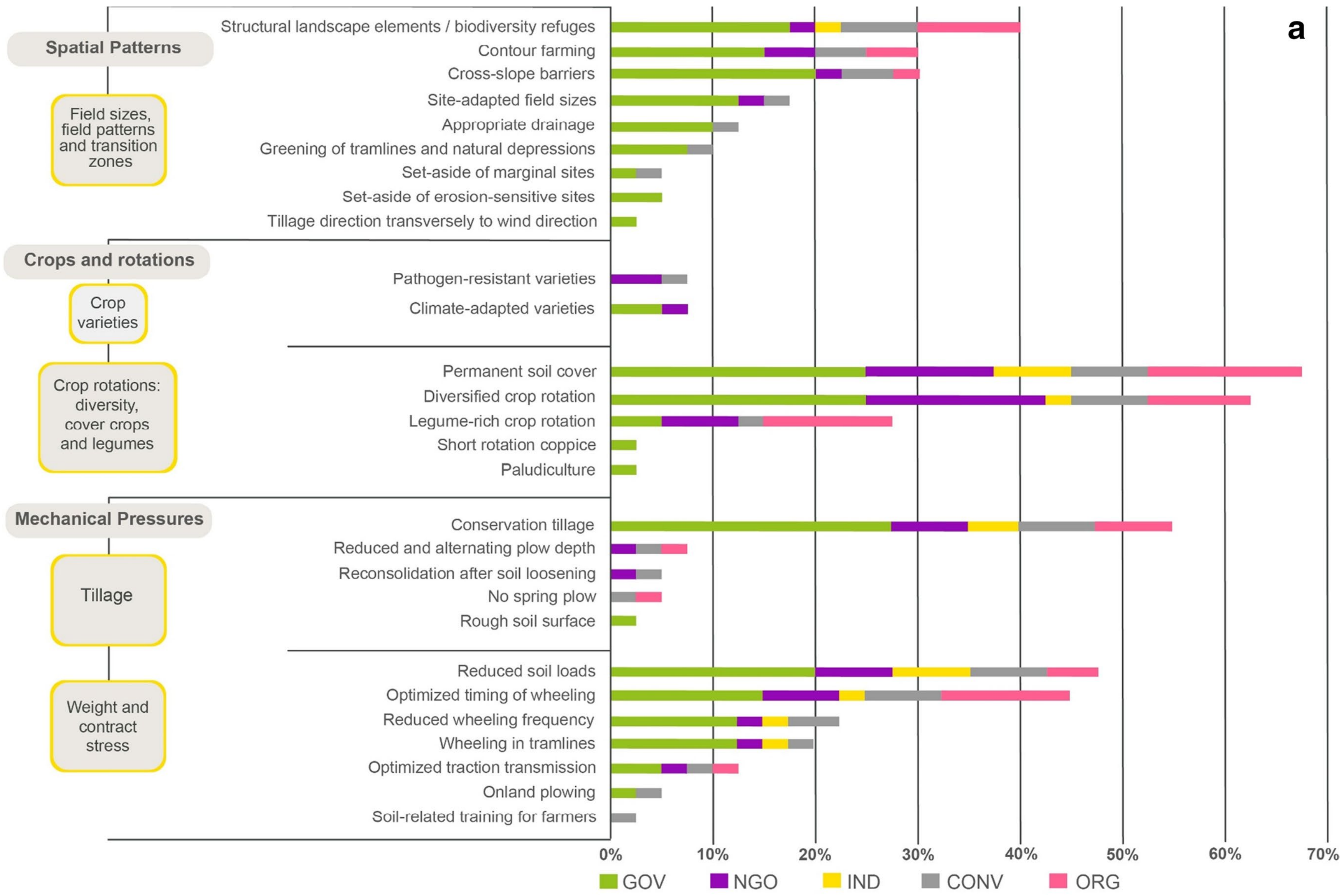
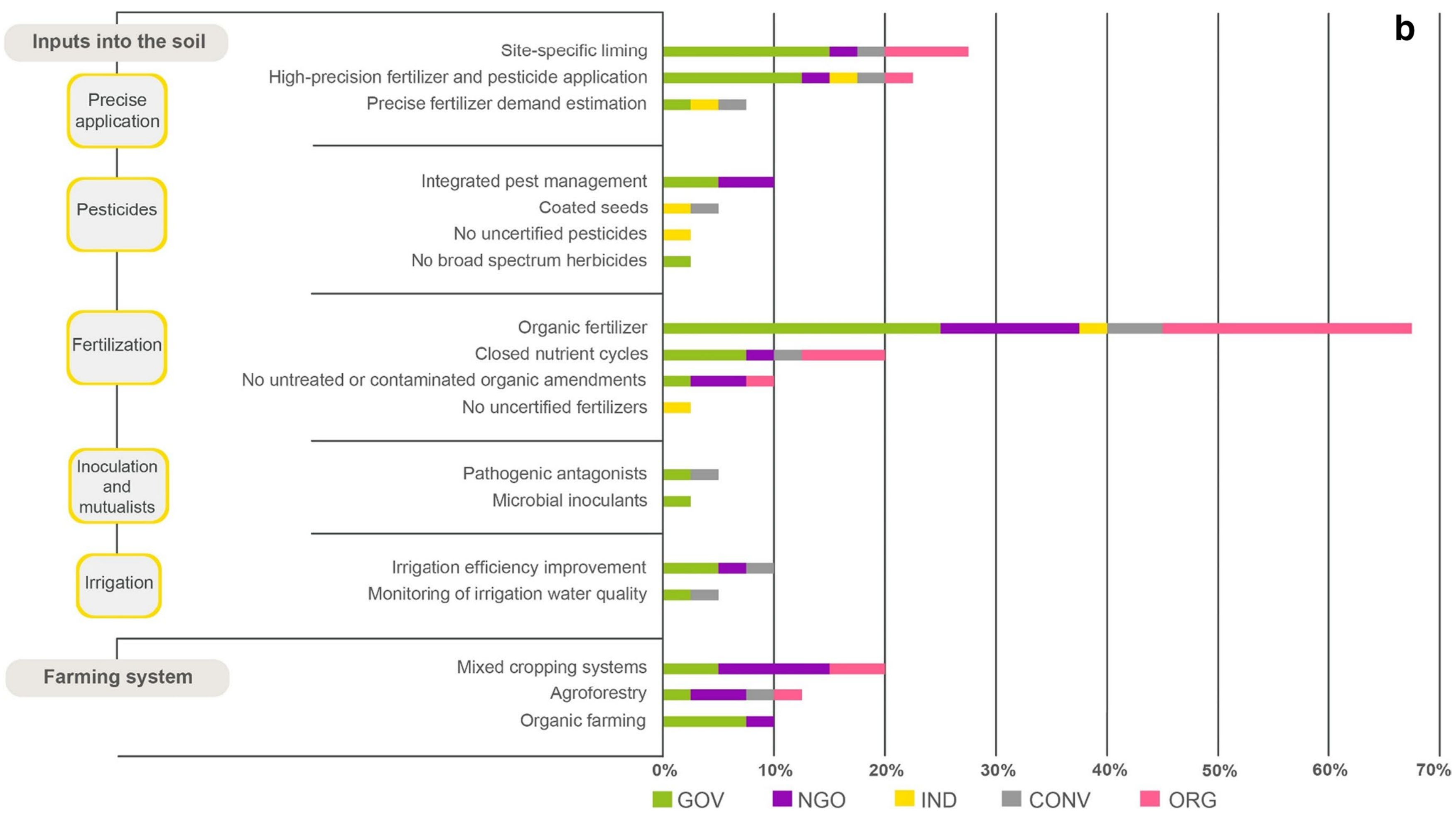


Fig. 3 Measures for sustainable soil management recommended in the analyzed stakeholder documents ($n = 40$). **a** Spatial patterns, crops and rotations, and mechanical pressures and **b** Inputs into the soil and farming system. Bars display the percentage of the 40 stakeholders that recommended the respective measure (2.5% = 1 stakeholder). Measures recommended by more than one-third of the stakeholders were included in the shortlist.



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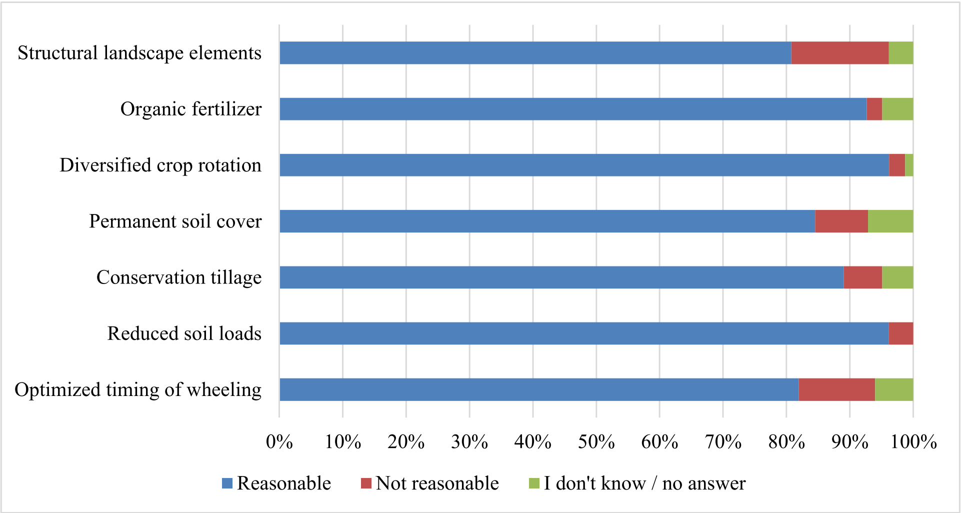


Fig. 4 Rating of reasonability of the shortlist of measures by German farmers ($n = 78$).

3 Results and discussion

3.1 Sustainable soil management measures recommended by stakeholders

Out of the 85 stakeholders we identified, 40 issued documents that met our selection criteria (Appendix Table 1). The share within each group was 58% for GOV (14/24), 58% for NGO (7/12), 22% for IND (5/23), 33% for CONV (5/15), and 82% for ORG (9/11).

Forty-six measures were identified in the document analysis (Fig. 3). Overall, "mechanical pressures" was the category most often addressed by the stakeholders, while "farming system" was the least addressed. The highest number of recommendations was recorded for "inputs into the soil." Of the groups, GOV stakeholders provided the highest number of recommendations.

Seven measures were recommended by more than one-third of the stakeholders and by stakeholders from all groups, namely, "structural landscape elements/biodiversity refuges," "permanent soil cover," "diversified crop rotation," "conservation tillage," "reduced soil loads," "optimized timing of wheeling," and "organic fertilizer" (Fig. 1). These measures formed our shortlist and are discussed further.

The largely differing numbers of documents per stakeholder group implied the risk of overrepresenting recommendations of groups with high numbers of documents (e.g., GOV). However, weighing the groups (i.e., calculating the arithmetic means ($\bar{x}$)

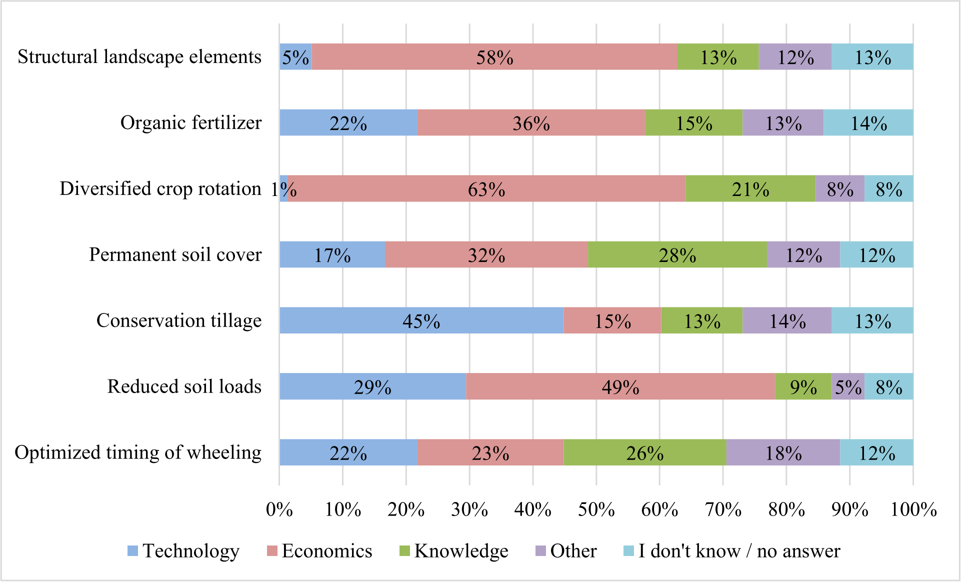


Fig. 5 Major barriers to the implementation of the shortlist of measures as perceived by German farmers ($n = 78$).

for each measure, based on equally weighted shares of agreement within each stakeholder group) caused only minimal changes in the long list and no changes in the shortlist.

3.2 Results of the farmer survey

Seventy-eight farmers replied to the survey. Respondents' locations were spread across Germany but mainly eastern states (the western federal states were poorly represented, possibly due to the severe floods in July 2021 that also affected agriculture (He et al. 2021)). Farm sizes were evenly distributed between farms smaller than 100 ha (36%), between 100 and 500 ha (38%) and larger than 500 ha (26%). Most respondents performed mixed arable and livestock farming (63%), while 27% performed only arable farming and 9% only livestock farming (other: 1%). The share of respondents performing organic farming was significantly higher (19%) than the German average (7.5%, cf. Destatis 2021). 78% performed conventional farming, and 3% performed both organic and conventional farming (Appendix Fig. 7)

All measures on the shortlist were considered reasonable by a vast majority of the survey respondents (Fig. 4). There were some differences between organic and conventional farming systems for some measures: "structural landscape elements," "permanent soil cover," and "optimized timing of wheeling" were considered more reasonable by organic farmers than conventional farmers (93.3/77.0%, 100.0/78.7%, and 93.3/77.0%, respectively); "Conservation tillage" was considered more reasonable by conventional farmers than by organic farmers (91.8/73.3%). Economics was considered the most important challenge to implementation for five of the seven measures, while for "conservation tillage," it was technology, and for "optimized timing of wheeling," the responses were equally distributed and no prevalent barrier could be identified (Fig. 5).

3.3 Discussion of measures

In this section, the shortlisted measures are discussed. For each measure, we first report the benefits that the stakeholder documents associate with it, discuss benefits and challenges in the context of scientific literature, and address suitability and barriers of implementation from farmers' perspective. This also allows us to analyze how well the measures address soil threats and soil functions, and how easily they can be implemented in existing farming systems.

3.3.1 Structural landscape elements/biodiversity refuges

Structural elements in agricultural fields include hedgerows, live fences, shelterbelts, ponds, nonproductive trees, flower strips, buffer strips, perennial wooden structures, or stone or terrace walls. In the stakeholder documents, implementing structural elements was considered a measure that contributes mainly to the soils' habitat function and addresses the threat of biodiversity decline, while it was often not clear from the documents whether this refers exclusively to soil organisms or also to aboveground biodiversity. Many documents also pointed to a link with the production function of soils because biodiversity is a functional element of soil fertility and because structural elements may provide shelter for pollinators and other beneficial species. Structural elements were also frequently linked to the prevention of wind and water erosion, as well as to preventing organic matter decline. To a lesser extent, positive effects of structural elements on water purification and retention and carbon sequestration were mentioned.

Research confirms that structural elements form important soil biodiversity reservoirs (Barthel et al. 2013) and are crucial for habitat connectivity and for the preservation of species that are incompatible with agriculture (Grass et al. 2019; Savić et al. 2021). They provide shelter for pollinators and predators and enhance their diversity and abundance (Dainese et al. 2017; van Vooren et al. 2017). The positive effect on predators may also reduce pesticide demand (Steingröver et al. 2010; Bianchi et al. 2008). Linear elements such as hedgerows, or flower strips can reduce soil erosion (Marshall and Moonen 2002), contribute to soil sediment and nutrient interception (Garratt et al. 2017), and thus benefit water quality (Tamburini et al. 2020). They can also significantly increase organic matter content and carbon stock in adjacent fields (van Vooren et al. 2017; Wojewoda and Russel 2003). Structural landscape elements are important for the intrinsic and functional diversity of agricultural landscapes (van den Berge et al. 2018; Grass et al. 2019) and therefore contribute directly and indirectly to soil multifunctionality.

While crop yield has been found to be more stable and more resilient to extreme events on fields with structural elements (Redhead et al. 2020), the overall yield is significantly reduced in close proximity to hedgerows and only slightly increased at farther distances (Raatz et al. 2019; van Vooren et al. 2017). Additionally, structural landscape elements occupy agricultural land, resulting in a trade-off between ecosystem service delivery and crop yield (van Vooren et al. 2017; Redhead et al. 2020). While seminatural habitats provide better pollination in agricultural fields, this cannot counterbalance the higher costs due to increased working time and fuel consumption (Clough et al. 2020; Kirchweger et al. 2020).

Accordingly, while 81% of the survey respondents deemed the implementation and preservation of structural landscape elements reasonable, economic constraints were perceived as the most important obstacle to their implementation (58%). Comments displayed a rather low motivation of farmers to implement and preserve structural elements and highlighted opportunity costs due to the occupied area and increased workload resulting from maintenance tasks. This might be especially relevant for small farms where taking land out of cultivation is more challenging than on larger farms (Wuepper et al. 2020). Several respondents commented that implementing structural landscape elements would only be possible with increased funding, while the application process for existing funding was perceived as complicated. In Europe, implementing landscape elements can be funded if they are registered as Ecological Focus Areas (EFA). However, due to strict requirements (e.g., regarding spatial dimensions) and a difficult administrative registration process, most farmers do not avail of this option (Zinngrebe et al. 2017).

Thus, improved funding schemes for structural elements may improve the adoption of this measure. It could easily be integrated into existing farming schemes, requiring only slight changes to management, such as respecting protective distances to structural elements when applying pesticides and fertilizers. Improved knowledge transfer about the long-term beneficial effects of diversely structured landscapes for yield stability and resilience might also foster a more positive attitude of farmers toward structural elements.

3.3.2 Organic fertilizer

This measure refers to an increased use of organic fertilizer or the addition of organic amendments. This includes the incorporation of straw and other crop residues, green manure, farmyard manure, solid dung, compost, sewage sludge, fermentation residues, horn manure and horn silica, or biochar. While some stakeholders recommended using mineral fertilizer as an additional option, others recommended completely avoiding mineral fertilizers. Several documents contained specifications, e.g., that the addition of organic amendments should be done in a balanced and context-adapted way, that knowledge about the nutrient composition of the organic amendments was required, or that the organic material should be incorporated into the soil (especially slurry). This measure was mostly linked to nutrient supply, humus preservation and formation, soil structure, and soil fertility. Organic fertilizers were considered to contribute to the improvement and maintenance of soil health, enabling good crop performance. Further linkages were made to the habitat function of soils, soil water holding capacity, erosion prevention, pest control, and the closing of nutrient cycles.

The use of organic fertilizer/adding diverse organic amendments to the soil has beneficial effects on soils, including improved biological functions, increased organic carbon, improved soil aggregate stability, more balanced release of N fertilizers, decreased nitrate leaching, pest and pathogen suppression, and improved crop yields; especially when regularly applied over long periods (Bailey and Lazarovits 2003; Crystal-Ornelas et al. 2021; Diacono and Montemurro 2011; Vida et al. 2020). However, the financial profitability of organic inputs is uncertain, especially in the short term (Constantin et al. 2015; Hijbeek et al. 2019), while excessive use of organic fertilizers is associated with nitrate leaching and groundwater pollution (Kühling et al. 2021). Furthermore, the regional concentration of specialized crop farms and livestock farms may cause shortages in the availability of animal manure, as transporting manure over long distances is economically unviable (Biberacher et al. 2009; Wezel et al. 2014) and results in high labor and energy costs (Sanchez et al. 2004). Another obstacle is the varying nutrient content of organic fertilizers which may lead farmers to opt for mineral fertilizer instead (Bert et al. 2009; Biberacher et al. 2009). Additionally, farmers also often lack knowledge of and experience with biobased fertilizers, e.g., regarding the timing of N availability to meet crop demands (Tur-Cardona et al. 2018; Sanchez et al. 2004). Tur-Cardona et al. (2018) found that farmers are more likely to choose organic fertilizers when they are clearly cheaper than mineral fertilizers. With the drastic increase of the energy prices since early 2022, organic fertilizers may become more attractive to farmers. However, solid forms of fertilizers and fertilizers that ensure a fast release of nutrients are typically preferred by farmers. While unprocessed manure is mostly cost-free for them, processed organic fertilizers (e.g., digestates) come in a more convenient form (e.g., pellets, less odorous) and without uncertainties regarding their nutrient content (Case et al. 2017; Tur-Cardona et al. 2018). However, heavily processed organic fertilizers may have reduced to no beneficial effects on soils as compared to mineral fertilizers (Löbmann et al. 2016).

Preferring organic over mineral fertilizer was deemed reasonable by 92% of the respondents, with no difference between conventional and organic farmers, but with a small difference between farms with livestock (96%) and farms without livestock (88%). Thirty-six percent of respondents considered economic constraints to be the most important obstacle to implementing this measure. In the comments, respondents pointed out decreasing livestock numbers in some regions, the low economic value of slurry as opposed to high costs, the effort needed for transportation and application, and high costs for machinery (trailing shoe, slurry injection). Legal requirements, such as the ban on spreading slurry on frozen soil and the amended German Fertilizer Ordinance in general were named as additional obstacles.

The expected positive effect on soil quality and associated co-benefits may function as a driver for implementations of this measure. The decision to increase organic fertilizer use may motivate specialized crop farms to switch to a mixed system that includes livestock, resulting in a complete redesign of the farming system (Wezel et al. 2014). More research is needed, e.g., on the linkage between organic input and pests, diseases, and weeds (Hijbeek et al. 2019), to reduce farmer uncertainty regarding the effects of organic amendments.

3.3.3 Diversified crop rotation

The level of specification for this measure differed between documents. Specific recommendations were to alternate leafy and cereal crops, winter and summer crops, and humus-decreasing and humus-enhancing crops; integrate catch crops, legumes, and deep-rooting crops; not grow corn directly after corn; and integrate rotational fallow land, rotational grazing, or planted set-aside areas for soil regeneration. More general recommendations were to establish crop rotations with at least 3 to 5 elements and pay attention to crop-specific cultivation pauses (NGO). Multiple benefits were associated with diversified crop rotations, such as increased biodiversity in agricultural landscapes and a reduction in pest pressure. This would reduce pesticide use and the associated risks of soil contamination and lead to more resilient crops. Furthermore, this measure was often linked to erosion control. Finally, diversified rotations also come with diversified root systems. This was considered to improve soil structure, increase fertility, reduce the risk of compaction and contribute to carbon sequestration and soil organic matter preservation.

Many studies confirm the positive effects of diverse crop rotations on soil biodiversity, microbial activity, soil structure, and aggregation, and consequently, on long-term fertility, habitat quality, erosion risk mitigation, and water retention (Ayalew et al. 2021; D'Acunto et al. 2018; Kay 1990; Kollas et al. 2015; Munkholm et al. 2013; Tiemann et al. 2015). However, effects depend on the specific management. For example, increases in carbon sequestration depend on crop choices, site-specific factors, and management (FAO and ITPS 2021; Scheffler and Wiegmann 2019). For beneficial effects on soil microbial communities and reduced pesticide use, rotations of 5 or more crops, including different crops and cultivation types such as winter and summer cereals, roots and tubers, legumes, or set-aside, have been recommended (Andert et al. 2016; Tiemann et al. 2015). In Europe, farms must already practice some degree of crop diversification to receive CAP greening payments; on the farm level, farms of a size between 10 and 30 ha need to grow at least 2 different crops, and farms larger than 30 ha need to grow at least 3 different crops, whereby the main crop must not cover more than 75% of the area (EC 2021). Accordingly, the majority of farms in Germany grow only 2 or 3 different crops at a time. Rotations are dominated by large proportions of maize and wheat, and little consideration is given to phytosanitary aspects (suitable precrop, cultivation pauses) (BMEL 2019; Steinmann and Dobers 2013).

Almost all survey respondents (96%) thought it was reasonable to diversify crop rotations. Farmers are aware of the ecological advantages of a more diverse crop rotation (Andert et al. 2016). However, their options are restricted by farm specialization, the availability of machinery on the farm, knowledge, market preferences, agricultural policies, and soil conditions. This results in (regional) preferences for specific crops (FAO and ITPS 2021; Steinmann and Dobers 2013). A majority of respondents (63%) considered economic constraints the most important obstacle to implementing this measure, followed by a lack of knowledge (21%). The comments revealed that farm type and size are also restricting factors: respondents stated that for small farms or farms growing fodder crops, there was little scope for diversifying crop rotations. Further obstacles were seen in uncertainties about revenues and yield stability for some crops.

Overall, implementing more diversified crop rotations would require substantial systemic changes for most farms in Germany. To motivate the implementation of this measure by German farmers, Andert et al. (2016) recommend providing more detailed information on the advantages of crop diversity, as well as a better design of financial and political incentives, rather than using command and control measures.

3.3.4 Permanent soil cover

Stakeholders recommended keeping soils covered as much as possible throughout the year. This can be achieved through catch crops, undersown crops, mulching (e.g., with crop residues), and optimization of the crop rotation (minimizing the time between harvest and sowing of the succeeding crop). More specific recommendations for catch crops were the use of seed mixtures and optimized seeding time to minimize the risk of crop failure due to pests, diseases, or weather extremes (e.g., dry periods). Furthermore, avoiding row crops (e.g., substituting corn with alfalfa or clover grass in biogas production) or performing mulch sowing for row crops, as well as perennial crops or dense sowing (e.g., choosing more dense cereals over winter wheat), was recommended. Possible economic disadvantages were mentioned for some of these management options, but also the possibility of reduced herbicide demand due to the weed suppressing function of soil cover. Continuous soil cover was mostly linked to the prevention of erosion. Furthermore, the increased organic matter input caused by this measure was considered to contribute to carbon sequestration and the prevention of soil organic matter decline, with positive effects on soil fertility and yield stability. Finally, this measure was associated with biodiversity preservation and an improved habitat function for above and belowground organisms.

Soil cover is a key factor in reducing the risk of wind and water erosion (Deumlich et al. 2006). In the universal soil loss equation (USLE), soil cover management is represented by the C-factor, which is the only factor that farmers can control (Auerswald et al. 2021). Cover crops are particularly favorable, since they provide soil cover during winter when soils would otherwise be barren. However, they come with additional costs for farmers (e.g., seeds, additional management) and their implementation may require changes to the established crop rotations (Sattler & Nagel 2010). In this regard, farmers may lack specific knowledge (Werner et al. 2017). Furthermore, continuous vegetation cover increases the overall water demand and reduces groundwater recharge (Lischeid and Natkhin 2011). Nonetheless, cover crops are among the most commonly applied EFA options in Europe (Zinngrebe et al. 2017), indicating a fair level of acceptance and practicability. Cover crops suppress weeds and thus reduce the need for tillage or herbicides (Brust et al. 2014; Gerhards & Schappert 2020). Furthermore, they increase the soil organic matter content (Poeplau & Don 2015), help recycle nitrogen in the upper soil layer (Hooker et al. 2008), improve soil structure and soil hydraulic properties, and have a beneficial effect on the habitat function of soils (Gerhards & Schappert 2020). The use of regional species and seed mixtures may result in more efficient soil cover, due to their adaptation to local conditions and a higher species diversity (Dybzinski et al. 2008; Nabel et al. 2021). Efficient soil cover can also be achieved by undersown crops (i.e., sowing a cover crop into the main crop after its establishment), while yields may be unaffected or even increase (Bergkvist et al. 2011; Johnson et al. 2021). Providing soil cover through mulching with crop residues (e.g., wheat straw) is a common practice in conservation tillage systems. Depending on the quantity and quality of residues, mulching can increase soil fertility, reduce fertilizer need, increase soil organic matter, and contribute to sustaining stable soil ecosystems (Kollas et al. 2015; Tiemann et al. 2015). However, mulching may also add to the persistence of residue-borne pathogens (Koivunen et al. 2018). This problem is likely to worsen with ongoing climate change (Fareed Mohamed Wahdan et al. 2020).

Maintaining soil cover was deemed reasonable by 83% of the respondents. Economic constraints (32%) and lack of knowledge (28%) were perceived as the most important obstacles to implementation. In the comments, farmers pointed to problems of water scarcity, phytosanitary problems, the planned ban on glyphosate in the EU, the need for appropriate machinery, and the incompatibility of this measure with specific crops.

Improved information for farmers on how to achieve continuous soil cover, distributed through, e.g., farm advisory systems, could address specific knowledge deficits and increase the adoption of this measure (Werner et al. 2017). However, implementing the different soil cover management options also requires systemic change. For cover crops, rotations may need to be adapted, while for the integration of undersown crops, compatible crops must be selected and specialized machinery, such as for combined harvesting and sowing, may be required (Sattler and Nagel 2010). Where water is a limiting factor, mulching may be preferable to continuous vegetation cover. In this case, diversified crop rotations may be necessary to avoid increased pest pressure (Buhre et al. 2009). Alternatively, farmers may consider switching to conservation tillage systems, as described in the following section.

3.3.5 Conservation tillage

Conservation tillage practices refer to management where mulch seeding, strip-till, or direct seeding replace conventional plowing to minimize mechanical disturbances of the soil. These practices were considered to improve the soils' carrying capacity; increase carbon sequestration; lower water losses; increase biological activity; prevent erosion, compaction, and capping; and reduce NO_3 losses. Opinions differed on how to manage the increased weed pressure associated with plowless systems. NGO and GOV stakeholders stated that farmers should not use broad-spectrum herbicides, or at least should not increase their herbicide use. Instead, the establishment of diverse plant communities and adapted crop rotations were suggested for countering weed pressure. In contrast, CONV, IND, and other GOV stakeholders considered conservation tillage practices to be inevitably linked with broadspectrum herbicide use, especially where a high degree of soil cover is maintained.

Conservation tillage measures can increase soil carrying capacity and reduce soil compaction, though effects differ depending on soil properties and types of management (Mirzavand and Moradi-Talebbeigi 2021; Pöhlitz et al. 2018). On the other hand, switching from conventional tillage to conservation tillage may also increase compaction, e.g., when crop rotations do not include deep-rooting crops and when the conditions for bioturbation by earthworms are unfavorable (Schlüter et al. 2018). Furthermore, heavy machinery can cause higher compaction in fields under conservation tillage than in plowed fields (Koch et al. 2008). Accordingly, Peigné et al. (2018) found that after 10 years of conservation tillage in an organic farming system on a sandy soil, soil compaction had increased, possibly due to intensive mechanical weed control measures. While it is widely acknowledged that conservation tillage enhances soil organic carbon (SOC) content in the upper soil layer, it is controversial whether this contributes to climate change mitigation, as the soil carbon stock in deeper soil layers can decrease (Lou et al. 2012;

Moreno et al. 2006). For the whole soil profile, Dimassi et al. (2014) report a net decrease in the soil organic carbon stock in reduced tillage systems under wet and warm conditions. Even where an increase in carbon stock is achieved, the climate benefits may be offset by higher N_2O emissions (Guenet et al. 2021; Mei et al. 2018). Conservation tillage practices have also been found to reduce soil erosion (Seitz et al. 2018). Obstacles to implementation mostly arise from trade-offs with weed pressure. As mechanical weed control through plowing is no longer applied, conservation tillage practices typically result in increased herbicide use and the combination of conservation tillage and use of broad-spectrum herbicides reduces labor requirements and working costs (Mal et al. 2015), while effects on soil biodiversity can be positive or negative for different invertebrate, microbial, and fungal taxa (Chávez-Ortiz et al. 2022; Froslev et al. 2022; van Capelle et al. 2012; Zaller et al. 2014). A trade-off with productivity may arise because it usually takes longer for untilled soils to warm up in spring, resulting in later crop growth and reduced mineralization (BLE 2020). The effects of conservation tillage cannot be generalized as they strongly depend on soil properties, climatic conditions, and farm management, such as the type of conservation tillage, cultivated crop, and weed management. Accordingly, the main influencing factors for adoption among European farmers are the biophysical conditions of an area and agricultural specialization (especially the cultivated crop), while the timing of sowing and harvest, as well as the socioeconomic conditions of the area, also plays a role (Bijttebier et al. 2018).

In the farmer survey, 88% of respondents considered conservation tillage a reasonable option, while 6% did not. Technology was considered the main obstacle to implementation (45%), followed by economic constraints (15%). For other reasons, farmers pointed to the planned ban on glyphosate use in Europe, which would limit the availability of broad-spectrum herbicides. Direct seeding was especially considered to depend on the application of these herbicides, although many farmers were aware of negative impacts on the environment. Where farmers cannot use broad-spectrum herbicides, as in organic farming systems, conservation tillage practices are difficult. Accordingly, among the organic farmers, a higher share (18%) rejected the measure.

Conservation tillage practices require specialized machinery and potentially different timing of farming operations, but they can easily be implemented without major systemic changes if broad-spectrum herbicides are used for weed control. For increased herbicide use to be avoided, successful application of conservation tillage requires a high standard of management, including thorough crop choice and rotations tailored to local soil and climatic conditions (Peigné et al. 2007), indicating substantial systemic change. Nabel et al. (2021) suggest that the use of broad-spectrum herbicides can be avoided in mulch seeding and that tillage could be used as a measure for pest control if all other options fail. In this case, they recommend immediately applying organic amendments to offset the carbon losses caused by the tillage and allow for a quick fauna restoration.

3.3.6 Reduced soil loads

A reduction in soil loads was recommended by 19 stakeholders (47.5%). Recommendations were (a) to reduce machinery weight, e.g., by using information and communication technology (ICT) and robotics (also to detect soil compaction), filling bunkers of harvesting machinery only partly, or performing umbilical slurry spreading where the slurry is pumped from the field edge to the tractor via a flexible pipeline, and (b) to ensure a larger contact area and better weight distribution, e.g., by using tire pressure regulation, twin tires, high floatation tires, caterpillar machinery, additional axles, crab-steering (offset track driving), or semi-mounted or attached devices. Unloading/transfer technology (conveyor belts) and the separation of field and street transport were recommended to facilitate optimal tire pressure for both purposes. Ideally, soil-protective properties should already be taken into account when purchasing machinery. A combination of multiple management options was considered to be most effective. The main benefit was considered to be the prevention of soil compaction, and only a few linkages to soil functions or other soil threats were described. Good soil structure, high earthworm activity, and avoided costs for potential soil loosening were mentioned as potential co-benefits of reduced weight pressure, while low tire pressure was considered to improve traction and thus reduce fuel costs and working time.

Many studies recommend the use of lighter machinery and an increase in the size of the contact area (Frelih-Larsen et al. 2018; Ledermüller et al. 2018; ten Damme et al. 2019), as well as low tire pressure (Brunotte and Lorenz 2015; ten Damme et al. 2019). The use of lightweight agricultural robots is still uncommon in Germany. Although some multifunctional models exist and are considered promising technologies (BMEL 2021; Scholz et al. 2014), farmers are generally skeptical about return on investment (Barnes et al. 2019). Findings by Rübcke von Veltheim and Heise (2020; 2021) indicate that the willingness of farmers to adopt robotics correlates with field size rather than with farm size. Reducing soil loads to prevent subsoil compaction is crucial, as the impacts of compaction are not immediately visible (Frelih-Larsen et al. 2018), and compaction can persist for decades or centuries (Berisso et al. 2012; Sharratt et al. 1998). Only in some cases can soils alleviate compaction quickly without human intervention (Badalíková, 2010). Prevention is also less costly than dealing with the consequences of subsoil compaction, such as decreased water infiltration, increased erosion risk, and decreased crop performance and farm profitability (Alakukku et al. 2003; Jamali et al. 2021).

Since both the weight pressure and frequency of wheeling are factors influencing soil compaction, the use of lighter machinery may not be beneficial if it leads to more frequent wheeling (Seehusen et al. 2019). For better weight distribution, twin tires are useful, but they add to the width of the vehicle. If this exceeds the maximum allowed on public streets, tires need to be mounted and dismounted at the field, which is costly and time consuming (KTBL 2011). Similarly, there is a weight limit for caterpillar machinery on German roads. Attached devices also improve weight distribution but require a larger area for turning maneuvers, making this measure only practicable on large fields. Field enlargement, however, is undesirable from the perspective of sustainable management. Additional axles are another option, although the alleviating effect on soil pressure is negated where manufacturers implement them to enable higher total machine weights (Alakukku et al. 2003). Low tire pressure is beneficial in the field but not feasible for street travel. Regulation systems can be used to adjust the pressure (Volk et al. 2011), although they are still expensive. Furthermore, while lowering the pressure is easy, increasing it requires time and energy, especially when high loads are carried (e.g., after harvest). Pressure regulation is therefore easier for slurry application, where the trailer is lighter when returning from the field, than for harvesting machinery (KTBL 2011). Finally, workers need to be trained and instructed on pressure regulation. Where management steps are executed by external contractors, the farmer's influence on this is limited (KTBL 2011).

In the farmer survey, 96% of respondents deemed a reduction in the weight pressure reasonable (not reasonable: 4%). Obstacles to implementation were considered to be mainly economic constraints (49%) or related to technology (29%). Switching from large machinery to lighter alternatives has economic consequences as it requires investment and may decrease cost and working time efficiency. Survey respondents stated that the high costs for specialized machinery would require the use of large areas to be profitable and pose a problem for smaller farms.

Thorsøe et al. (2019) discourage a general weight limit for machinery because it would unnecessarily restrict farmer options at times when the soil is dry and able to carry high loads. The proposed management options for this measure are mostly technical, requiring little systemic change but typically investment in specialized machinery. In this regard, the measure of "filling harvesting bunkers only partly" is an exception as new machinery is not required. However, it is time consuming due to more frequent unloading and therefore costly.

3.3.7 Optimized timing of wheeling

A total of 18 stakeholders (45%) recommended optimized timing of wheeling, meaning that field traffic should be avoided when the soil is too wet to prevent compaction and maintain a good soil structure. For this purpose, it was recommended that soil consistency/soil humidity be measured and machinery and working capacities be reserved to be able to perform agronomic operations only at suitable times. Some stakeholders recommended combining this measure with other management options for optimal compaction prevention, e.g., conservation tillage for better soil carrying capacity, the use of wide tires, and the use of the crab-steering (offset track driving) mode. Others pointed out the importance of this measure for compaction prevention.

Several studies highlight the importance of this measure for preventing subsoil compaction (Alakukku et al. 2003; van den Akker and Soane 2005). Since the carrying capacity of soil is strongly influenced by soil moisture, there is a risk of compaction when soils are wet. The weight pressure of machinery may then exceed the soil's carrying capacity, especially for management tasks characterized by high soil loads, such as slurry distribution or harvest (Thorsøe et al. 2019). Preventing compaction can also reduce the risk of water erosion (Fullen 1985). However, tight work schedules may force farmers to use machinery under unfavorable soil moisture conditions, as specialized machinery needs a high degree of utilization to be profitable (Lorenz et al. 2016). Further barriers to sustainably addressing subsoil compaction are a lack of knowledge and problem awareness, the preference of farmers to fulfill short-term contracts over long-term soil fertility management, outsourcing of responsibilities (e.g., farming operations done by contractors), and the complex nature of subsoil compaction (Thorsøe et al. 2019). Marx and Jacobs (2020) also note that the collaboration between scientists and practitioners is still insufficient; furthermore, farmers experience top-down communication of recommendations for compaction prevention that are often generalizing or difficult to understand, which limits the acceptance of recommended measures.

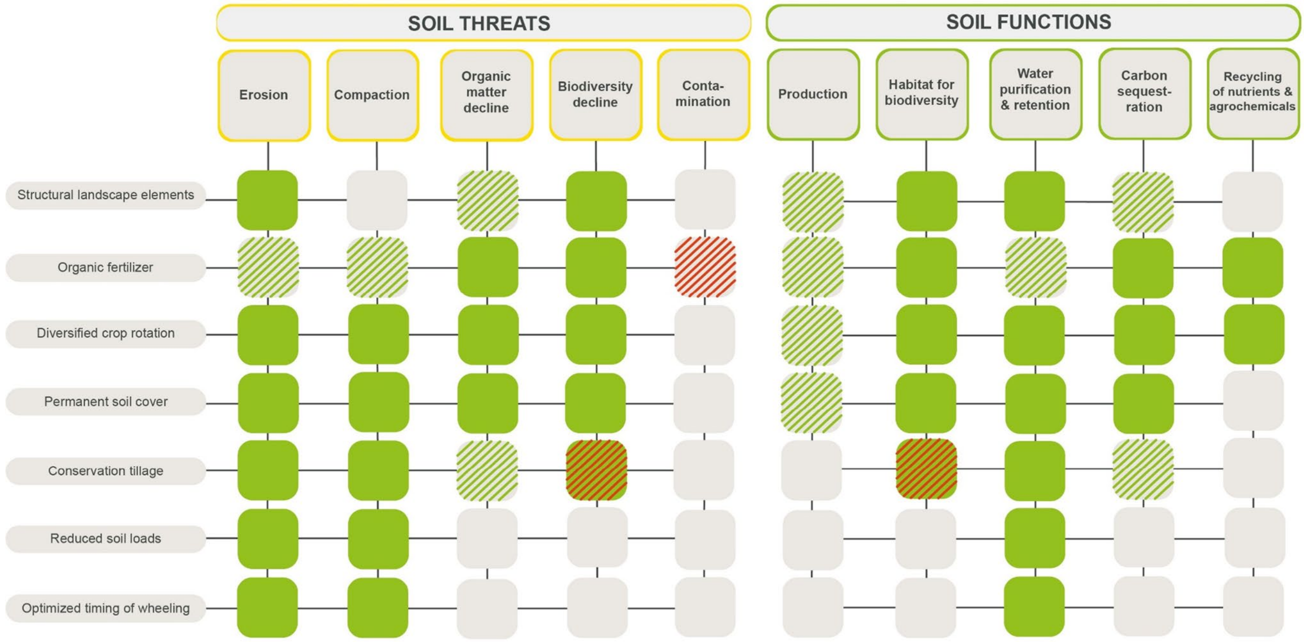
Eighty-one percent of the survey respondents rated the optimization of the wheeling timing as reasonable, while 13% did not. Responses related to the main obstacles to implementation were evenly distributed among knowledge (26%), economic constraints (23%), and technology (22%). Farmers commented that (unpredictable) weather conditions complicate the implementation of this measure. Further problems were seen in the time requirements and organizational challenges, such as outsourcing operations to contractors, or when farming was practiced as a secondary job, which would sometimes make it impossible to take soil conditions into account. Reserving or increasing working capacities was commented to be unrealistic for economic reasons.

To promote the implementation of this measure, Thorsøe et al. (2019) recommend the development of a legal framework that incentivizes and enables sustainable management decisions. They stress the need for systemic solutions that include not only farmers but also other stakeholders such as farming education institutions, machinery manufacturers, contractors and retailers. Technical solutions are also under development. These include decision-support tools and concepts that define the timeframe for the workability of the soil, considering the weather, compaction risk, and machine utilization (Edwards et al. 2016; Ledermüller et al. 2018; Lorenz et al. 2016; Obour et al. 2017). They could help optimize the timing of wheeling as much as possible, without requiring a substantial systemic change for farms. However, for regions where seasonal high soil moisture levels regularly occur, Chamen et al. (2003) recommend rather choosing crops that require little work during this time, which implies greater changes for farms.

3.4 Synthesis of measures

Our analysis of the effects, co-benefits, and trade-offs of the proposed management measures shows that benefits for soil functions and reductions in soil threats are highly interlinked. Most of the proposed measures improve multiple soil functions simultaneously, and many of the soil threats and functions are addressed by multiple measures (Fig. 6). Erosion and water purification and retention are addressed by all seven measures. Compaction, biodiversity and organic matter/carbon sequestration are addressed by five to six of the seven measures. The production function was not affected negatively by any of the shortlisted measures. However, economic trade-offs may exist since many of the measures may be less profitable. For example, diversified crop rotations may require more costly seeds and the cultivation of less profitable crops, or land area for production may be reduced if structural landscape elements are established or if green manure is cultivated for organic fertilizers. Soil contamination was the only soil threat that was not addressed by the shortlist of measures. Conversely, some organic fertilizers bear the potential to contribute to the contamination of soils, e.g., through heavy metals in recycled sewage sludge (Tarpani et al. 2020).

While reducing soil loads and optimizing the timing of wheeling are suitable options for preventing soil compaction, these measures do not provide many other benefits to agricultural soils, indicating that technological solutions alone are not sufficient for sustainable soil management. On the other hand, the measures that have multiple beneficial effects on soils, namely, "organic fertilization," "diversified crop rotation," and "permanent soil cover," are also the measures that will involve the greatest systemic changes in the farming system. Organic fertilization requires growing green manure and/or developing ways to obtain animal-based organic



	SOIL THREATS					SOIL FUNCTIONS				
	Erosion	Compaction	Organic matter decline	Biodiversity decline	Contamination	Production	Habitat for biodiversity	Water purification & retention	Carbon sequestration	Recycling of nutrients & agrochemicals
Structural landscape elements	🟩	⬜	▨	🟩	⬜	▨	🟩	🟩	▨	⬜
Organic fertilizer	▨	▨	🟩	🟩	▧	▨	🟩	▨	🟩	🟩
Diversified crop rotation	🟩	🟩	🟩	🟩	⬜	▨	🟩	🟩	🟩	🟩
Permanent soil cover	🟩	🟩	🟩	🟩	⬜	▨	🟩	🟩	🟩	⬜
Conservation tillage	🟩	🟩	▨	▧	⬜	⬜	▧	🟩	▨	⬜
Reduced soil loads	🟩	🟩	⬜	⬜	⬜	⬜	⬜	🟩	⬜	⬜
Optimized timing of wheeling	🟩	🟩	⬜	⬜	⬜	⬜	⬜	🟩	⬜	⬜

Fig. 6 Linkages between the shortlist of measures and soil threats and soil functions. Green squares = positive linkage (i.e., mitigation of soil threats/fostering of soil functions). Grey squares = no linkages made. Striped squares: linkage weak or contested (green = positive, red = negative).

fertilizers, i.e., introducing livestock into the farm system or at least establishing a collaboration with livestock farms. Diversifying crop rotations and maintaining continuous soil cover require adaptations of crop rotations and workflows and will affect farm revenues. These examples support the general finding about the importance of diversification for the improvement of ecosystem services in agricultural systems (Tamburini et al. 2020). In the long term, for "structural landscape elements," "organic fertilization," "diversified crop rotation," and "permanent soil cover," a positive impact on the production function is even possible. The soil function "recycling of nutrients" is only supported by "organic fertilization" and "diversified crop rotation." This highlights the importance of these two measures, especially for achieving closed nutrient cycles, which is considered a crucial element of sustainable agriculture but at the same time linked to major systemic changes not only at the farm level, but also for the entire agrifood system (Magdoff et al. 1997).

3.5 Methodology discussion

The objectives of this study required several simplifications. All stakeholder documents meeting our selection criteria were treated equally, irrespective of differences in quality, level of detail, or influence of the respective stakeholders. Furthermore, the categorization of stakeholder groups did not account for within-group heterogeneities. Finally, the bundling of recommendations under a common term always implies a loss of information. However, these simplifications allowed the recommendations to be sorted, overlaps between stakeholder opinions to be identified, and widely accepted management measures to be derived.

It is possible that the keyword-based search did not identify all relevant documents. The number of documents found differed greatly between stakeholder groups, which may reflect differences in the awareness of the need for more sustainable soil management, a group's role with regard to promoting or implementing such management, or specific biases and interests. Overall, the number of documents per group was considered too low to allow for a detailed analysis of within-group and between-group differences.

4 Conclusion

Governance for more sustainable soil management is easiest to implement and most effective where proposed measures meet with approval across a wide set of stakeholder groups. Out of the multitude of measures recommended by stakeholders, we derived a shortlist of seven measures for which there is a high degree of agreement, and which are proposed by stakeholders from all investigated stakeholder groups. The measures address all soil functions and all soil threats except for contamination. For this soil threat, additional measures will be necessary.

Many of the measures address more than one threat or function, and most of the measures have multiple benefits. However, the measures require varying degrees of systemic change in the farm system to be implemented, even more so since the measures should ideally be implemented in combination. Diversification is one of the key principles behind more sustainable soil management. Our findings support the common evidence that a diversification of approaches and cropping systems is the preferable way to maintain and restore soil health and to meet future challenges of food security and climate change.

In our survey, the vast majority of farmers supported the shortlist of measures. Obstacles to implementation were mainly considered to be economic constraints and partly technical, while a lack of knowledge was seen as only a minor obstacle. These results provide valuable information for the formulation of effective governance options.

While this work was able to identify agricultural measures with wide support across all stakeholder groups, the definition of these measures is still too broad for direct implementation in a farming or policy context. Future research should seek to specify these measures and tailor them to varying local conditions and farming contexts.

5 Appendix

5.1 Stakeholder documents

Table 1 Stakeholder documents included in the analysis. German stakeholder names and document titles are translated to English.

Stakeholder group	Stakeholder	Function/activity field	Document title	Reference
Public governance and institutions (GOV)	Food and Agriculture Organization of the United Nations (FAO)	International specialized organization	Voluntary guidelines for sustainable soil management	FAO (2017)
	UN Global Compact	International network	Principles for sustainable soil management	UN Global Compact (2016)
	European Commission (EC)	International authority	EU Biodiversity Strategy for 2030. Bringing nature back into our lives	EC (2020)
	German Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU)	National ministry	Sustainability in arable farming. Key points for a farming strategy	BMU (2019)
	German Federal Ministry for Nutrition and Agriculture (BMEL)	National ministry	Discussion paper: farming strategy 2035. Perspectives for productive and diverse crop cultivation	BMEL (2019)
	Ministry for the Environment, Nature Conservation, and Transport of Baden-Wuerttemberg (LUBW)	Regional ministry	Soil, soils, soil protection	LUBW (2015)
	Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of North Rhine-Westphalia (MKULNV)	Regional ministry	Climate change and soil. Impacts of global warming on the soil as plant habitat	MKULNV (2011)
	Bavarian State Ministry for Nutrition, Agriculture and Forestry	Regional ministry	(1) Soil: maintenance of site-specific humus values (2) Improving erosion control – limiting runoff in agricultural areas: recommendations for action of the working group erosion control (3) Soil: soil erosion, soil compaction, soil water balance	(1) StMELF (2021b); (2) StMELF (2017); (3) (StMELF (2021a)
	State Office of Brandenburg for rural development, agriculture and rezoning	Regional ministry	Arable soil use on steep slopes. Recommendations for the prevention of pesticide and fertilizer inputs into surface water bodies	LELF (2012)
	Hessian ministry for environment, climate protection, agriculture, and consumer protection	Regional ministry	Soil protection in Hesse. Establishment of buffer strips	HMUKLV (2021)
	Saxonian state institute for agriculture	Regional ministry	Soil protection in agriculture	SLUL (2004)

Table 1 (continued)

Stakeholder group	Stakeholder	Function/activity field	Document title	Reference
	Commission for soil protection at the German Federal Environment Agency	Advisory council	Soil and biodiversity – demands to policy-makers	KBU (2020)
	aid Information Service	Advisory council	Good farming practices. Soil management and soil protection	aid Infodienst (2015)
	Association for Technology and Structures in Agriculture (KTBL)	Advisory council	Protect soil and save costs	KTBL (2011)
Nongovernmental organizations (NGO)	Association for environment and nature protection Germany (BUND)	Environmental NGO	(1) Soil atlas. Data and facts about fields, land, and soil (2) Uncover the fraudulent labeling: glyphosate is neither soil protective nor climate protective (3) Soil protection in agriculture	(1) BUND (2015); (2) BUND and Beste (2019); (3) BUND (2021)
	Greenpeace	Environmental NGO	Timetable agricultural transition 2050. Ecologically sustainable agriculture in Germany	Wirz et al. (2017)
	Global Nature Fund	Environmental NGO	Biodiversity factsheet arable farming: sugar beet cropping	Global Nature Fund (2018)
	INKOTA association, Oxfam Germany and MISEREOR	Social NGO	Better different, different better. Shaping the transition of nutrition with agroecology	Heuser et al. (2016)
	Interest group for healthy soil	Environmental interest group	Healthy soil in our opinion. Position paper	IG gesunder Boden e.V. (2020)
	Movement of the catholic land youth	Environmental/social interest group	Living soils — understand, respect, protect	KLJB (2014)
	German Nature Protection Association (DNR)	Environmental interest group	Opinion of the Environmental Umbrella Association DNR to the Arable Farming Strategy	DNR (2020)
Agricultural industry (IND)	Industry Association Agriculture (IVA)	Agrochemicals	Agriculture contributes to soil protection	IVA (2021)
	Bayer AG	Agrochemicals	Our position on preservation and reestablishment of biodiversity in agriculture and forestry	Bayer AG (2020)
	Bridgestone EUROPE EV	Agricultural machinery	The tyre as a key for cost savings	Bridgestone EUROPE EV (2021)
	AMAZONE	Agricultural machinery	Solutions for the activity fields soil protection and crop diversity	Amazone (2021)
	Economic Sugar Association (WVZ) & Sugar Industry Association (VdZ)	Sugar industry	(1) Beet cropping: general (2) Beet cropping: soil protection (3) Beet cropping: pest management (4) Beet cropping: fertilization (5) Beet cropping: harvesting	(1) WVZ and VdZ (2020a) (2) WVZ and VdZ (2020b) (3) (WVZ & VdZ, 2020e) (4) WVZ and VdZ (2020c) (5) WVZ and VdZ (2020d)

Table 1 (continued)

Stakeholder group	Stakeholder	Function/activity field	Document title	Reference
Conventional farming associations (CONV)	Central Committee of German Agriculture (chair: German Farmers‘ Federation (DBV))	Conventional farming association	Arable farming strategy of German agriculture	ZDL (2018)
	German Chambers of Agriculture (VLK)	Conventional farming association	Climate change and agriculture. Adaptation strategies in arable farming.	VLK (2019)
	German Agricultural Association (DLG)	Conventional farming association	(1) DLG Factsheet 431: strengthening biodiversity in arable farming (2) DLG Factsheet 344: soil-protective use of agricultural machinery	(1) DLG-Ausschuss für Ackerbau et al. (2018) (2) Brandhuber et al. (2016)
	Association of the German Land Youth and BUND youth	Conventional farming association and environmental NGO	Joint vision on the future of agriculture by BUND youth and the Association of the German Land Youth	Bund der deutschen Landjugend e.V. and BUNDjugend (2021)
	German Maize Committee (DMK)	Corn cropping association	Soil management	DMK (2021)
Organic farming associations (ORG)	Council of the European Union	Organic farming label	Council Regulation (EC) No. (834/2007) of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91	Council Regulation (EC) No. 834/2007)
	Demeter	Organic farming label	General regulations for production	Demeter e.V. (2021)
	Naturland association for organic farming	Organic farming label	Naturland Production Regulations, version of 05/2020	Naturland Verband für ökologischen Landbau e.V. (2020)
	Gäa	Organic farming label	Gäa production regulations	Gäa e.V. (2021)
	BIO.VEG.AN.	Organic farming label	Biocyclic-vegan regulations, version 2.0	BIO.VEG.AN. (2017)
	Bioland e.V.	Organic farming label	Bioland regulations, version of 24 Nov 2020	Bioland e.V. (2020)
	Biokreis e.V.	Organic farming label	Production regulations. Version of April 2021	Biokreis e.V. (2021)
	Biopark e.V.	Organic farming label	Production regulations organic farming	Biopark e.V. (2017)
	Bundesanstalt für Landwirtschaft und Ernährung (BLE) Referat 413 (Projektgruppe Ökolandbau)[3]	Organic farming information portal	(1) Soil fertility (2) Soil bacteria as useful helpers in arable farming (3) Reduced tillage – protects soil and climate (4) Reduced pressure for the soil (5) Target-conform soil management	(1) BLE (2019) (2) BLE (2020a) (3) BLE (2020b) (4) BLE (2020c) (5) BLE (2020d)

References: Stakeholder documents

aid Infodienst (2015) Gute fachliche Praxis. Bodenbewirtschaftung und Bodenschutz (2nd ed.). aid Infodienst Ernährung, Landwirtschaft, Verbraucherschutz e. V.

Amazone (2021) Lösungen für die Handlungsfelder Bodenschutz und Kulturpflanzenvielfalt. Amazonen-Werke H. Dreyer SE, Co. KG.

Bayer AG (2020) Unser Standpunkt zur Erhaltung und Wiederherstellung der Biodiversität in Land- und Forstwirtschaft. https://www.bayer.com/de/nachhaltigkeit/position-zur-biodiversitaet. Accessed 3 Dec 2020

BIO VEG AN (2017) Biozyklisch-vegane Richtlinien, Version 2.0. Biozyklisch-Veganer Anbau e.V. - BIO.VEG.AN.

Biokreis e.V. (2021) Richtlinien Erzeugung, April 2021. Biokreis Verband für Ökologischen Landbau und gesunde Ernährung e.V.

Bioland e.V. (2020) Bioland Richtlinien, Fassung vom 24, November 2020. Bioland e.V. Verband für organisch-biologischen Landbau.

Biopark e.V. (2017) Erzeugerrichtlinie ökologischer Landbau, Biopark e.V.

BLE (2019) Bodenfruchtbarkeit. https://www.oekolandbau.de/landwirtschaft/pflanze/grundlagen-pflanzenbau/boden/bodenfruchtbarkeit/. Accessed 20 June 2020

BLE (2020a) Bodenbakterien als nützliche Helfer im Pflanzenbau. https://www.oekolandbau.de/landwirtschaft/pflanze/grundlagen-pflanzenbau/boden/bodenbakterien-helfer-im-pflanzenbau/. Accessed 20 June 2020

BLE (2020b) Reduzierte Bodenbearbeitung – schont Boden und Klima. https://www.oekolandbau.de/landwirtschaft/pflanze/grundlagen-pflanzenbau/boden/reduzierte-bodenbearbeitung/. Accessed 20 June 2021

BLE (2020c) Weniger Druck für den Boden. https://www.oekolandbau.de/landwirtschaft/pflanze/grundlagen-pflanzenbau/boden/bodenverdichtungen-vermeiden/. Accessed 20 June 2020

BLE (2020d). Zielkonforme Bodenbearbeitung. https://www.oekolandbau.de/landwirtschaft/pflanze/grundlagen-pflanzenbau/boden/bodenbearbeitung/. Accessed 20 June 2020

BMU (2019) Nachhaltigkeit im Ackerbau - Eckpunkte für eine Ackerbaustrategie. Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit.

BMEL (2019) Diskussionspapier: Ackerbaustrategie 2035. Perspektiven für einen produktiven und vielfältigen Pflanzenbau Bundesministerium für Ernährung und Landwirtschaft (BMEL), Referat 711.

Brandhuber R, Demmel M, Koch H-J, Brunotte J (2016) DLG-Merkblatt 344: Bodenschonender Einsatz von Landmaschinen. DLG e.V., Fachzentrum Landwirtschaft & Bayerische Landesanstalt für Landwirtschaft (LfL).

Bridgestone Europe EV (2021) Der Reifen als Schlüssel für Kosteneinsparungen. BRIDGESTONE EUROPE NV/SA AG department. https://www.bridgestone-agriculture.eu/hubfs/ebooks/Productivity_eBook_DE.pdf?__hstc=225730053.881d39e7436d7900f73e7d76c418efc3.1615812261983.1615812261983.1615812261983.1&__hssc=225730053.2.1615812261983&__hsfp=93788232&hsCtaTracking=0ec0c912-3e3c-40eb-a42a-0abcfdf517a5%7C24bf6b57-48d8-4dc3-8f6a-48cc4f178ebe.

Bund der deutschen Landjugend e.V., BUNDjugend (2021) Gemeinsame Vision zur Zukunft der Landwirtschaft von BUNDjugend und Bund der Deutschen Landjugend. https://www.landjugend.de/fileadmin/Redaktion/Downloads/Positionen/2021_Zukunftsbild_BUNDjugend-BDL.PDF. Accessed 10 May 2021

BUND (Bund für Umwelt- und Naturschutz Deutschland e.V.) (2021) Bodenschutz in der Landwirtschaft. http://bodenschutz.bund.net/themen/bodenschutz_in_der_landwirtschaft/. Accessed 01 July 2021

BUND (Bund für Umwelt- und Naturschutz Deutschland e.V.) (2015) Bodenatlas. Daten und Fakten über Acker, Land und Erde. Heinrich-Böll-Stiftung.

BUND (Bund für Umwelt- und Naturschutz Deutschland e.V.), Beste A (2019) Den Etikettenschwindel enttarnen: Glyphosat ist weder Boden- noch Klimaschutzmittel! http://bodenschutz.bund.net/fileadmin/bundgruppen/bcmsbodenschutz/pdf/Factsheets_Glyphosat.pdf. Accessed 01 July 2021

Council Regulation (EC) No. (834/2007) of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91. Official Journal of the European Union L189 50. https://bit.ly/3hARc34

Demeter e.V. (2021) Allgemeine Regelungen Erzeugung. In: Richtlinien 2021 Erzeugung und Verarbeitung. Richtlinien für die Zertifizierung »Demeter« und »Biodynamisch«. Demeter e.V. https://bit.ly/3eUgF5D

DLG-Ausschuss für Ackerbau, DLG-Arbeitsgruppe Nachhaltige Landwirtschaft, Erdle K, Packeiser M, Wiesner J (2018) DLG-Merkblatt 431: Artenvielfalt und Biodiversität stärken im Ackerbau. DLG e.V., Fachzentrum Landwirtschaft. https://www.dlg.org/fileadmin/downloads/landwirtschaft/themen/publikationen/merkblaetter/dlg-merkblatt_431.pdf.

DMK (Deutsches Maiskomitee e.V.) (2021) Bodenbearbeitung. https://www.maiskomitee.de/Produktion/Anbau/Bodenbearbeitung. Accessed 01 July 2021

DNR (Deutscher Naturschutzring) e.V. (2020). Stellungnahme des Umweltdachverbands Deutscher Naturschutzring zur Ackerbaustrategie. https://backend.dnr.de/sites/default/files/Publikationen/2020-08-DNR-Stellungnahme-Ackerbaustrategie_01.pdf. Accessed 25 Nov 2020

EC (2020) EU Biodiversity Strategy for 2030. Bringing nature back into our lives. COM/2020/380 final, European Commission.

FAO (2017) Voluntary Guidelines for Sustainable Soil Management". Food and Agriculture Organization of the United Nations.

Gäa e.V. (2021) Gäa-Richtlinien Erzeugung. Gäa e.V. - Vereinigung ökologischer Landbau.

Global Nature Fund (2018) Biodiversity Fact Sheet Ackerbau: Anbau von Zuckerrüben. https://www.globalnature.org/bausteine.net/f/8790/LIFEFoodBiodiversity_FactSheet_Zuckerr%c3%bcben_online.pdf?fd=0. Accessed 25 Nov 2020

Heuser A, Thomsen B, Wilhelm B, Rocha C, Pohl C, Díaz I, Urhahn J, Minh LN, Mendonça M, Schutte OD, Tittonell P, Gioia P, Volz P, Schneider S, Tanzmann S, Sachs W (2016) Besser anders, anders besser. Mit Agrarökologie die Ernährungswende gestalten. INKOTA-netzwerk e. V., Oxfam Deutschland e. V., MISEREOR e. V., Aachen & Berlin, Germany.

HMUKLV (2021) Bodenschutz in Hessen. Anlage von Erosionsschutzstreifen. Hessisches Ministerium für Umwelt, Klimaschutz, Landwirtschaft und Verbraucherschutz.

IG gesunder Boden e.V. (2020) Gesunder Boden aus unserer Sicht. Positionspapier der IG gesunder Boden e.V. https://www.ig-gesunder-boden.de/Portals/0/doc/Positionspapiere/2020-11-13_Positionspapier-GesunderBodenausunsererSicht.pdf. Accessed 04 April 2021

IVA (Industrieverband Agrar) (2021) Landwirtschaft trägt zum Bodenschutz bei. https://www.iva.de/umwelt/landwirtschaft-traegt-zum-bodenschutz-bei. Accessed 08 October 2020

KBU (2020) Boden und Biodiversität – Forderungen an die Politik. Kommission Bodenschutz beim Umweltbundesamt (KBU).

KLJB (Katholische Landjugendbewegung) (2014) Lebendige Böden — verstehen, respektieren, schützen. https://www.kljb.org/themen/laendliche-entwicklung/bodenfruchtbarkeit/. Accessed 20 Nov 2020

KTBL (2011) Boden schonen und Kosten senken. Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. KTBL (89).

LELF (2012) Ackerbauliche Bodennutzung bei starker Hangneigung. Empfehlungen zur Vorbeugung von Pflanzenschutzmittel- und Nährstoffeinträgen in Oberflächengewässer. Landesamt für Ländliche Entwicklung, Landwirtschaft und Flurneuordnung.

LUBW (2015) Boden, Böden, Bodenschutz. Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Referat 22 - Boden, Altlasten, Document ID:51992.

MKULNV (2011) Klimawandel und Boden. Auswirkungen der globalen Erwärmung auf den Boden als Pflanzenstandort. Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen.

Naturland Verband für ökologischen Landbau e.V. (2020) Naturland Richtlinien Erzeugung, Stand 05/2020. Naturland Verband für ökologischen Landbau e.V.

SLUL (2004) Bodenschutz in der Landwirtschaft. Sächsische Landesanstalt für Landwirtschaft.

StMELF (2021a) Boden: Bodenerosion, Bodenverdichtung, Bodenwasserhaushalt. https://www.lfl.bayern.de/iab/boden/031249/index.php. Accessed 4 July 2021

StMELF (2021b) Boden: Erhaltung der standorttypischen Humuskennwerte. https://www.lfl.bayern.de/iab/boden/031172/index.php. Accessed 4 July 2021

StMELF (2017) Erosionsschutz verbessern – Abfluss in der landwirtschaftlichen Flur bremsen: Handlungsempfehlungen der Arbeitsgruppe Erosionsschutz. Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten.

TLL (2003) Empfehlungen für die Untersuchung und Bewertung von Wasser zur Bewässerung von gärtnerischen und landwirtschaftlichen Fruchtarten in Thüringen. Thüringer Landesanstalt für Landwirtschaft.

UN Global Compact (2016) Principles for Sustainable Soil Management. https://d306pr3pise04h.cloudfront.net/docs/issues_doc%2Fagriculture_and_food%2Fsoil-principles.pdf. Accessed 5 April 2021

VLK (Verband der Landwirtschaftskammern) (2019) Klimawandel und Landwirtschaft. Anpassungsstrategien im Ackerbau. Verband der Landwirtschaftskammern (VLK).

Wirz A, Kasperczyk N, Thomas F (2017) Kursbuch Agrarwende 2050. Ökologisierte Landwirtschaft in Deutschland. Greenpeace e.V.

WVZ (Wirtschaftliche Vereinigung Zucker e.V.), VdZ (Verein der Zuckerindustrie e.V.) (2020a) Rübenanbau: Allgemein. http://www.zuckerverbaende.de/ruebe-zucker/anbau-und-erzeugung/ruebenanbau.html. Accessed 10 November 2020

WVZ (Wirtschaftliche Vereinigung Zucker e.V.), VdZ (Verein der Zuckerindustrie e.V.) (2020b) Rübenanbau: Bodenschutz. http://www.zuckerverbaende.de/ruebe-zucker/anbau-und-erzeugung/ruebenanbau/bodenschutz.html. Accessed 10 November 2020

WVZ (Wirtschaftliche Vereinigung Zucker e.V.), VdZ (Verein der Zuckerindustrie e.V.) (2020c). Rübenanbau: Düngung. http://www.zuckerverbaende.de/ruebe-zucker/anbau-und-erzeugung/ruebenanbau/duengung.html. Accessed 11 November 2020

WVZ (Wirtschaftliche Vereinigung Zucker e.V.), VdZ (Verein der Zuckerindustrie e.V.) (2020d, 11 November 2020). Rübenanbau: Erntetechnik. http://www.zuckerverbaende.de/ruebe-zucker/anbau-und-erzeugung/ruebenanbau/erntetechnik.html. Accessed 11 November 2020

WVZ (Wirtschaftliche Vereinigung Zucker e.V.), VdZ (Verein der Zuckerindustrie e.V.) (2020e, 11 November 2020). Rübenanbau: Pflanzenschutz. http://www.zuckerverbaende.de/ruebe-zucker/anbau-und-erzeugung/ruebenanbau/pflanzenschutz.html. Accessed 11 November 2020

ZDL (Zentralausschuss der Deutschen Landwirtschaft) (2018) Ackerbaustrategie der deutschen Landwirtschaft. Zentralausschuss der Deutschen Landwirtschaft.

5.2 Statistical survey data

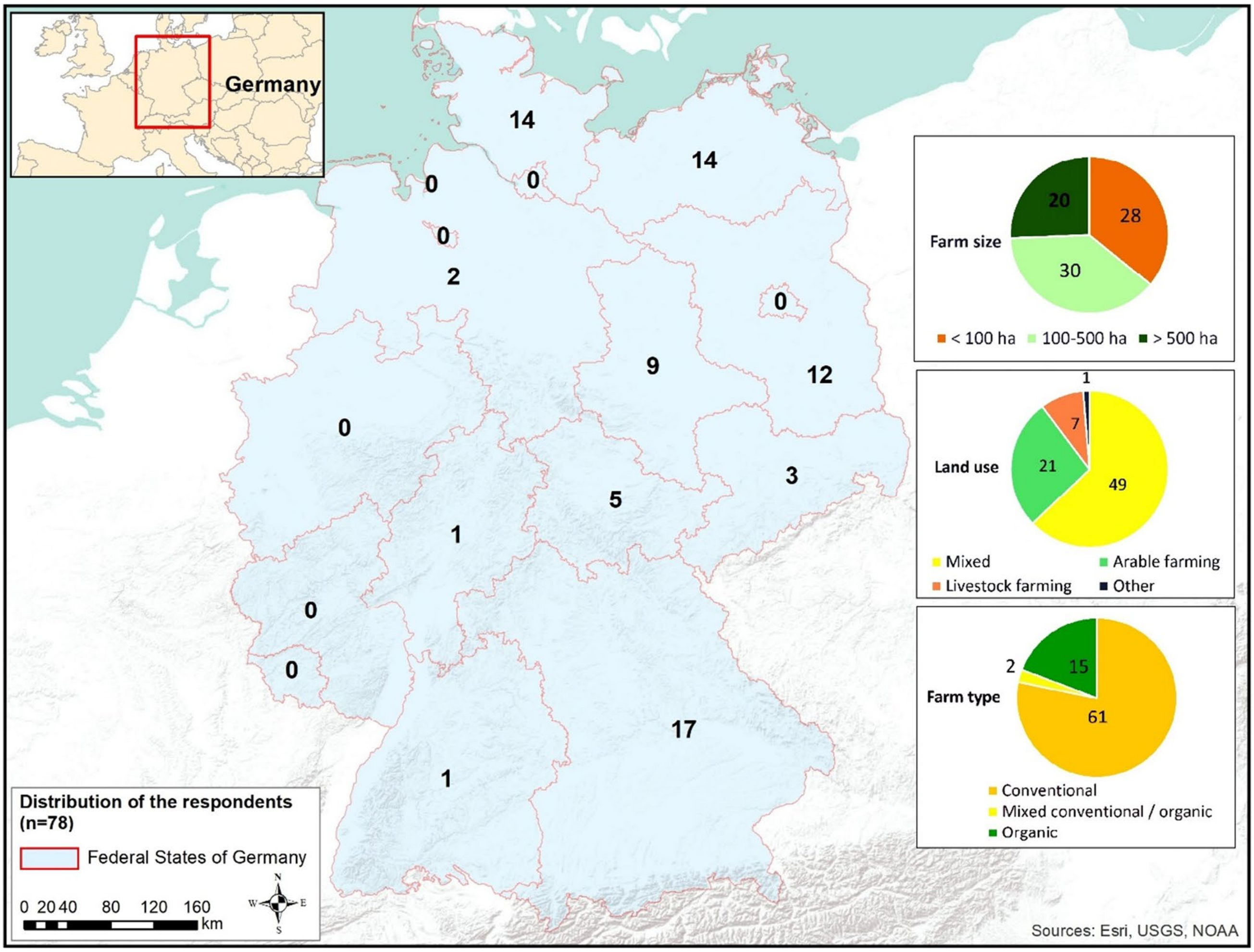


Fig. 7 Statistical data from the farmer survey.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

Conflict of interest Katharina Helming is on the editorial board of Agronomy for Sustainable Development and receives no compensation as member of the board of directors. She was not involved in the review of this article. The authors declare no further competing interests.

References

Alakukku L, Weisskopf P, Chamen WCT, Tijink FGJ, van der Linden JP, Pires S, Sommer C, Spoor G (2003) Prevention strategies for field traffic-induced subsoil compaction: a review: part 1. Machine/soil Interactions. Soil Tillage Res 73(1):145–160. https://doi.org/10.1016/S0167-1987(03)00107-7

Altobelli F, Vargas R, Corti G, Dazzi C, Montanarella L, Monteleone A, Caon L, Piazza MG, Calzolari C, Munafò M, Benedetti A (2020) Improving soil and water conservation and ecosystem services by sustainable soil management practices: from a global to an Italian soil partnership. Ital J Agron 15(4):293–298. https://doi.org/10.4081/ija.2020.1765

Andert S, Bürger J, Stein S, Gerowitt B (2016) The influence of crop sequence on fungicide and herbicide use intensities in North German arable farming. Eur J Agron 77:81–89. https://doi.org/10.1016/j.eja.2016.04.003

Atkinson R, Flint J (2004) Snowball sampling. In: Lewis-Beck M, Bryman AE, Liao TF (eds) The SAGE encyclopedia of social science research methods. SAGE Publications, Thousand Oaks, London, New Delhi, pp 1043–1044

Auerswald K, Ebertseder F, Levin K, Yuan Y, Prasuhn V, Plambeck NO, Menzel A, Kainz M (2021) Summable C factors for contemporary soil use. Soil Tillage Res 213:105155. https://doi.org/10.1016/j.still.2021.105155

Ayalew DA, Deumlich D, Šarapatka B (2021) Agricultural landscape-scale C factor determination and erosion prediction for various crop rotations through a remote sensing and GIS approach. Eur J Agron 123:126203. https://doi.org/10.1016/j.eja.2020.126203

Badalíková B (2010) Influence of soil tillage on soil compaction. In: Dedousis AP, Bartzanas T (eds), Soil engineering. Springer, Berlin, Heidelberg, pp. 19-30. https://doi.org/10.1007/978-3-642-03681-1_2

Bailey KL, Lazarovits G (2003) Suppressing soil-borne diseases with residue management and organic amendments. Soil Tillage Res 72(2):169–180. https://doi.org/10.1016/S0167-1987(03)00086-2

Barnes AP, Soto I, Eory V, Beck B, Balafoutis AT, Sanchez B, Vangeyte J, Fountas S, van der Wal T, Gómez-Barbero M (2019) Influencing incentives for precision agricultural technologies within European arable farming systems. Environ Sci Policy 93:66–74. https://doi.org/10.1016/j.envsci.2018.12.014

Barthel S, Crumley CL, Svedin U (2013) Biocultural refugia: combating the erosion of diversity in landscapes of food production. Ecol Soc 18(4):71. https://doi.org/10.5751/es-06207-180471

Bergkvist G, Stenberg M, Wetterlind J, Båth B, Elfstrand S (2011) Clover cover crops under-sown in winter wheat increase yield of subsequent spring barley—effect of N dose and companion grass. Field Crops Res 120(2):292–298. https://doi.org/10.1016/j.fcr.2010.11.001

Berisso FE, Schjønning P, Keller T, Lamandé M, Etana A, de Jonge LW, Iversen BV, Arvidsson J, Forkman J (2012) Persistent effects of subsoil compaction on pore size distribution and gas transport in a loamy soil. Soil Tillage Res 122:42–51. https://doi.org/10.1016/j.still.2012.02.005

Bert V, Jacques V, Xavier G (2009) Effect of uncertainty on farmers decision making: case of animal manure use. APSTRACT 3(5–6):7–13. https://doi.org/10.19041/APSTRACT/2009/5-6/1

Bianchi FJJA, Goedhart PW, Baveco JM (2008) Enhanced pest control in cabbage crops near forest in The Netherlands. Landsc Ecol 23(5):595–602. https://doi.org/10.1007/s10980-008-9219-6

Biberacher M, Warnecke S, Brauckmann H-J, Broll G (2009) A linear optimisation model for animal farm manure transports in regions with high intensity animal farming 18th World IMACS/MODSIM Congress, Cairns, Australia

Bijttebier J, Ruysschaert G, Hijbeek R, Werner M, Pronk AA, Zavattaro L, Bechini L, Grignani C, ten Berge H, Marchand F, Wauters E (2018) Adoption of non-inversion tillage across Europe: use of a behavioural approach in understanding decision making of farmers. Land Use Policy 78:460–471. https://doi.org/10.1016/j.landusepol.2018.05.044

BLE (2020) Reduzierte Bodenbearbeitung – schont Boden und Klima. https://www.oekolandbau.de/landwirtschaft/pflanze/grundlagen-pflanzenbau/boden/reduzierte-bodenbearbeitung/. Accessed 20 June 2021

BMEL (2019) Diskussionspapier: Ackerbaustrategie 2035. Perspektiven für einen produktiven und vielfältigen Pflanzenbau Bundesministerium für Ernährung und Landwirtschaft (BMEL), Referat 711

BMEL (2021) Digitalisierung in der Landwirtschaft. Bundesministerium für Ernährung und Landwirtschaft (BMEL), Referat 821.

Brunotte J, Lorenz M (2015) Anpassung der Lasteinträge landwirtschaftlicher Maschinen an die Verdichtungsempfindlichkeit von Böden–Wunschtraum oder bereits Realität. Tagungsband "Jahr des Bodens" Schwere Maschinen, enge Fruchtfolgen, Gärreste – eine Gefahr für die Bodenfruchtbarkeit? Fachtagung 13, Kulturlandschaftstag, Würzburg, Germany

Brust J, Claupein W, Gerhards R (2014) Growth and weed suppression ability of common and new cover crops in Germany. Crop Prot 63:1–8. https://doi.org/10.1016/j.cropro.2014.04.022

Buhre C, Kluth C, Bürcky K, Märländer B, Varrelmann M (2009) Integrated control of root and crown rot in sugar beet: combined effects of cultivar, crop rotation, and soil tillage. Plant Dis 93(2):155–161. https://doi.org/10.1094/pdis-93-2-0155

Case SDC, Oelofse M, Hou Y, Oenema O, Jensen LS (2017) Farmer perceptions and use of organic waste products as fertilisers — a survey study of potential benefits and barriers. Agric Syst 151:84–95. https://doi.org/10.1016/j.agsy.2016.11.012

Chamen T, Alakukku L, Pires S, Sommer C, Spoor G, Tijink F, Weisskopf P (2003) Prevention strategies for field traffic-induced subsoil compaction: a review: part 2. Equipment and field practices. Soil Tillage Res 73 (1):161-174. https://doi.org/10.1016/S0167-1987(03)00108-9

Chávez-Ortiz P, Tapia-Torres Y, Larsen J, García-Oliva F (2022) Glyphosate-based herbicides alter soil carbon and phosphorus dynamics and microbial activity. Appl Soil Ecol 169:104256. https://doi.org/10.1016/j.apsoil.2021.104256

Clough Y, Kirchweger S, Kantelhardt J (2020) Field sizes and the future of farmland biodiversity in European landscapes. Conserv Lett 13(6):e12752. https://doi.org/10.1111/conl.12752

Constantin J, Dürr C, Tribouillois H, Justes E (2015) Catch crop emergence success depends on weather and soil seedbed conditions in interaction with sowing date: a simulation study using the SIMPLE emergence model. Field Crops Res 176:22–33. https://doi.org/10.1016/j.fcr.2015.02.017

Crittenden SJ, Poot N, Heinen M, van Balen DJM, Pulleman MM (2015) Soil physical quality in contrasting tillage systems in organic and conventional farming. Soil Tillage Res 154:136–144. https://doi.org/10.1016/j.still.2015.06.018

Crystal-Ornelas R, Thapa R, Tully KL (2021) Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: A meta-analysis. Agric Ecosyst Environ 312:107356. https://doi.org/10.1016/j.agee.2021.107356

D'Acunto L, Andrade JF, Poggio SL, Semmartin M (2018) Diversifying crop rotation increased metabolic soil diversity and activity of the microbial community. Agric Ecosyst Environ 257:159–164. https://doi.org/10.1016/j.agee.2018.02.011

Dainese M, Montecchiari S, Sitzia T, Sigura M, Marini L (2017) High cover of hedgerows in the landscape supports multiple ecosystem services in Mediterranean cereal fields. J Appl Ecol 54(2):380–388. https://doi.org/10.1111/1365-2664.12747

Destatis (2021) Betriebsgrößenstruktur landwirtschaftlicher Betriebe nach Bundesländern. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Landwirtschaftliche-Betriebe/Tabellen/betriebsgroessenstruktur-landwirtschaftliche-betriebe.html#fussnote-4-122912. Accessed 13 July 2021

Deumlich D, Funk R, Frielinghaus M, Schmidt W-A, Nitzsche O (2006) Basics of effective erosion control in German agriculture. J Plant Nutr Soil Sci 169(3):370–381. https://doi.org/10.1002/jpln.200621983

Diacono M, Montemurro F (2011) Long-term effects of organic amendments on soil fertility. In: Lichtfouse E, Hamelin M, Navarrete M, Debaeke P (eds), Sustainable agriculture volume 2. Springer Netherlands, pp 761-786. doi:https://doi.org/10.1007/978-94-007-0394-0_34

Dimassi B, Mary B, Wylleman R, Labreuche J, Couture D, Piraux F, Cohan J-P (2014) Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agric Ecosyst Environ 188:134–146. https://doi.org/10.1016/j.agee.2014.02.014

Dybzinski R, Fargione JE, Zak DR, Fornara D, Tilman D (2008) Soil fertility increases with plant species diversity in a long-term biodiversity experiment. Oecologia 158(1):85–93. https://doi.org/10.1007/s00442-008-1123-x

European Commission (2021) Sustainable land use (greening). https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/income-support/greening_en. Accessed 09 Sep 2021

European Commission (2006) Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - Thematic Strategy for Soil Protection [SEC(2006)620] [SEC(2006)1165] /* COM/2006/0231 final */. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52006DC0231. Accessed 11 Jan 2022

Edwards G, White DR, Munkholm LJ, Sørensen CG, Lamandé M (2016) Modelling the readiness of soil for different methods of tillage. Soil Tillage Res 155:339–350. https://doi.org/10.1016/j.still.2015.08.013

EEA (European Environment Agency) (2019) Soil and United Nations Sustainable Development Goals. https://www.eea.europa.eu/signals/signals-2019-content-list/infographics/soil-and-united-nations-sustainable/view. Accessed 17 Aug 2020

FAO, ITPS (2015) Status of the World's Soil Resources (SWSR) — main report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils

FAO, ITPS (2021) Recarbonizing global soils: a technical manual of recommended management practices. Volume 3: Cropland, grassland, integrated systems and farming approaches — practices overview. https://doi.org/10.4060/cb6595en

Fareed Mohamed Wahdan S, Hossen S, Tanunchai B, Schädler M, Buscot F, Purahong W (2020) Future climate significantly alters fungal plant pathogen dynamics during the early phase of wheat litter decomposition. Microorganisms 8(6):908. https://doi.org/10.3390/microorganisms8060908

Frelih-Larsen A, Bowyer C, Albrecht S, Keenleyside C, Kemper M, Nanni S, Naumann S, Mottershead RD, Langrebe R, Andersen E, Banfi P, Bell S, Brémere I, Cools J, Herbert S, Iles A, kampa E, Kettunen M, Lukacova Z, Vidaurre R (2017) Updated inventory and assessment of soil protection policy instruments in EU member states [Final Report to DG Environment]. https://www.researchgate.net/publication/341909850_Updated_Inventory_and_Assessment_of_Soil_Protection_Policy_Instruments_in_EU_Member_States. Accessed 11 Jan 2022

Frelih-Larsen A, Hinzmann M, Ittner S (2018) The 'invisible' subsoil: an exploratory view of societal acceptance of subsoil management in Germany. Sustainability 10(9):3006. https://doi.org/10.3390/su10093006

Froslev TG, Nielsen IB, Santos SS, Barnes CJ, Bruun HH, Ejrnaes R (2022) The biodiversity effect of reduced tillage on soil microbiota. Ambio 51(4):1022–1033. https://doi.org/10.1007/s13280-021-01611-0

Fullen MA (1985) Compaction, hydrological processes and soil erosion on loamy sands in east Shropshire. England. Soil Tillage Res 6(1):17–29. https://doi.org/10.1016/0167-1987(85)90003-0

Garratt MPD, Senapathi D, Coston DJ, Mortimer SR, Potts SG (2017) The benefits of hedgerows for pollinators and natural enemies depends on hedge quality and landscape context. Agric Ecosyst Environ 247:363–370. https://doi.org/10.1016/j.agee.2017.06.048

Gerhards R, Schappert A (2020) Advancing cover cropping in temperate integrated weed management. Pest Manag Sci 76(1):42–46. https://doi.org/10.1002/ps.5639

Ginzky H, Grimski D, Frauenstein J, Glante F, Ehlers K, Marx K (2018) Notwendigkeit von bodenschutzbezogenen Regelungen auf EU-Ebene. Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/notwendigkeit-von-bodenschutzbezogenen-regelungen. Accessed 12 Jan 2022

Glæsner N, Helming K, De Vries W (2014) Do current European policies prevent soil threats and support soil functions? Sustainability 6(12):9538–9563. https://doi.org/10.3390/su6129538

Grass I, Loos J, Baensch S, Batáry P, Librán-Embid F, Ficiciyan A, Klaus F, Riechers M, Rosa J, Tiede J, Udy K, Westphal C, Wurz A, Tscharntke T (2019) Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. People and Nature 1(2):262–272. https://doi.org/10.1002/pan3.21

Guenet B, Gabrielle B, Chenu C, Arrouays D, Balesdent J, Bernoux M, Bruni E, Caliman J-P, Cardinael R, Chen S, Ciais P, Desbois D, Fouche J, Frank S, Henault C, Lugato E, Naipal V, Nesme T, Obersteiner M, Pellerin S, Powlson DS, Rasse DP, Rees F, Soussana J-F, Su Y, Tian H, Valin H, Zhou F (2021) Can N2O emissions offset the benefits from soil organic carbon storage? Glob Chang Biol 27(2):237–256. https://doi.org/10.1111/gcb.15342

Gunreben M (2005) Dealing with soil threats in Lower Saxony. Germany. Land Degrad Dev 16(6):547–550. https://doi.org/10.1002/ldr.709

He K, Yang Q, Shen X, Anagnostou EN (2021) Brief communication: Western Europe flood in 2021-mapping agriculture flood exposure from SAR. Nat Hazards Earth Syst Sci 22:2921–2927. https://doi.org/10.5194/nhess-2021-307

Helming K, Daedlow K, Hansjürgens B, Koellner T (2018) Assessment and governance of sustainable soil management. Sustainability 10(12):4432. https://doi.org/10.3390/su10124432

Hijbeek R, Pronk AA, van Ittersum MK, Verhagen A, Ruysschaert G, Bijttebier J, Zavattaro L, Bechini L, Schlatter N, ten Berge HFM

(2019) Use of organic inputs by arable farmers in six agro-ecological zones across Europe: Drivers and barriers. Agric Ecosyst Environ 275:42–53. https://doi.org/10.1016/j.agee.2019.01.008

Hooker KV, Coxon CE, Hackett R, Kirwan LE, O'Keeffe E, Richards KG (2008) Evaluation of cover crop and reduced cultivation for reducing nitrate leaching in Ireland. J Environ Qual 37(1):138–145. https://doi.org/10.2134/jeq2006.0547

Horschig T, Schaubach K, Sutor C, Thrän D (2020) Stakeholder perceptions about sustainability governance in the German biogas sector. Energ Sustain Soc 10(1):36. https://doi.org/10.1186/s13705-020-00270-5

Jamali H, Nachimuthu G, Palmer B, Hodgson D, Hundt A, Nunn C, Braunack M (2021) Soil compaction in a new light: know the cost of doing nothing — a cotton case study. Soil Tillage Res 213:105158. https://doi.org/10.1016/j.still.2021.105158

Johnson KL, Kandel HJ, Samarappuli DP, Berti MT (2021) Interseeding camelina and rye in soybean with varying maturity provides soil cover without affecting soybean yield. Agron 11(2):353. https://doi.org/10.3390/agronomy11020353

Juerges N, Hansjürgens B (2018) Soil governance in the transition towards a sustainable bioeconomy — a review. J Clean Prod 170:1628–1639. https://doi.org/10.1016/j.jclepro.2016.10.143

Kay BD (1990) Rates of change of soil structure under different cropping systems. In: Stewart BA (ed), Advances in soil science. Springer, New York, NY, pp 1-52. https://doi.org/10.1007/978-1-4612-3316-9_1

Keesstra SD, Bouma J, Wallinga J, Tittonell P, Smith P, Cerdà A, Montanarella L, Quinton JN, Pachepsky Y, van der Putten WH, Bardgett RD, Moolenaar S, Mol G, Jansen B, Fresco LO (2016) The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. Soil 2(2):111–128. https://doi.org/10.5194/soil-2-111-2016

Kibblewhite MG, Ritz K, Swift MJ (2008) Soil health in agricultural systems. Philos Trans R Soc 363(1492):685–701. https://doi.org/10.1098/rstb.2007.2178

Kirchweger S, Clough Y, Kapfer M, Steffan-Dewenter I, Kantelhardt J (2020) Do improved pollination services outweigh farm-economic disadvantages of working in small-structured agricultural landscapes? — development and application of a bio-economic model. Ecol Econ 169:106535. https://doi.org/10.1016/j.ecolecon.2019.106535

Koch H-J, Heuer H, Tomanová O, Märländer B (2008) Cumulative effect of annually repeated passes of heavy agricultural machinery on soil structural properties and sugar beet yield under two tillage systems. Soil Tillage Res 101(1):69–77. https://doi.org/10.1016/j.still.2008.07.008

Koivunen EE, Tully KL, Swett CL (2018) Co-managing soil and plant pathogens: effects of organic amendments on soil fertility and fungal pathogen survival. Plant Soil 432(1):171–189. https://doi.org/10.1007/s11104-018-3779-2

Kollas C, Kersebaum KC, Nendel C, Manevski K, Müller C, Palosuo T, Armas-Herrera CM, Beaudoin N, Bindi M, Charfeddine M, Conradt T, Constantin J, Eitzinger J, Ewert F, Ferrise R, Gaiser T, Cortazar-Atauri IGd, Giglio L, Hlavinka P, Hoffmann H, Hoffmann MP, Launay M, Manderscheid R, Mary B, Mirschel W, Moriondo M, Olesen JE, Öztürk I, Pacholski A, Ripoche-Wachter D, Roggero PP, Roncossek S, Rötter RP, Ruget F, Sharif B, Trnka M, Ventrella D, Waha K, Wegehenkel M, Weigel H-J, Wu L (2015) Crop rotation modelling—a European model intercomparison. Eur J Agron 70:98–111. https://doi.org/10.1016/j.eja.2015.06.007

KTBL (2011) Boden schonen und Kosten senken. Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. KTBL (89)

Kühling I, Beiküfner M, Vergara M, Trautz D (2021) Effects of adapted N-fertilisation strategies on nitrate leaching and yield performance of arable crops in North-Western Germany. Agron 11(1):64. https://doi.org/10.3390/agronomy11010064

Lal R (2009) Laws of Sustainable Soil Management. In: Lichtfouse E, Navarrete M, Debaeke P, Véronique S, Alberola C (eds), Sustainable agriculture. Springer Netherlands, pp 9-12. https://doi.org/10.1007/978-90-481-2666-8_2

Ledermüller S, Lorenz M, Brunotte J, Fröba N (2018) A multi-data approach for spatial risk assessment of topsoil compaction on arable sites. Sustainability 10(8):2915. https://doi.org/10.3390/su10082915

Lischeid G, Natkhin M (2011) The potential of land-use change to mitigate water scarcity in Northeast Germany – a Review. Erde 142:97–113

Löbmann MT, Vetukuri RR, de Zinger L, Alsanius BW, Grenville-Briggs LJ, Walter AJ (2016) The occurrence of pathogen suppressive soils in Sweden in relation to soil biota, soil properties, and farming practices. Appl Soil Ecol 107:57–65. https://doi.org/10.1016/j.apsoil.2016.05.011

Lorenz M, Brunotte J, Vorderbrügge T, Brandhuber R, Koch H-J, Senger M, Fröba N, Löpmeier F-J (2016) Adaption of load input by agricultural machines to the susceptibility of soil to compaction — principles of soil conserving traffic on arable land. Appl Agric Forestry Res 66:101–144. https://doi.org/10.3220/LBF1473334823000

Lou Y, Xu M, Chen X, He X, Zhao K (2012) Stratification of soil organic C, N and C: N ratio as affected by conservation tillage in two maize fields of China. CATENA 95:124–130. https://doi.org/10.1016/j.catena.2012.02.009

Magdoff F, Lanyon L, Liebhardt B (1997) Nutrient cycling, transformations, and flows: implications for a more sustainable agriculture. In: Sparks DL (ed), Advances in agronomy. Academic Press, pp 1-73. https://doi.org/10.1016/S0065-2113(08)60600-8

Mal P, Schmitz M, Hesse JW (2015) Economic and environmental effects of conservation tillage with glyphosate Use: a Case Study of Germany. Outlooks Pest Manag 26(1):24–27. https://doi.org/10.1564/v26_feb_07

Marshall E, Moonen A (2002) Field margins in northern Europe: their functions and interactions with agriculture. Agric Ecosyst Environ 89(1–2):5–21. https://doi.org/10.1016/S0167-8809(01)00315-2

Marx K, Jacobs A (2020) SOILAssist-Teilprojekt ‚Akzeptanz und Implementierung': Analyse behördlicher Handlungsempfehlungen zur Vermeidung von Bodenverdichtung auf Ackerböden. Thünen Working Paper, 160. https://doi.org/10.3220/WP1604915142000

Mei K, Wang Z, Huang H, Zhang C, Shang X, Dahlgren RA, Zhang M, Xia F (2018) Stimulation of N_2O emission by conservation tillage management in agricultural lands: A meta-analysis. Soil Tillage Res 182:86–93. https://doi.org/10.1016/j.still.2018.05.006

Mirzavand J, Moradi-Talebbeigi R (2021) Relationships between field management, soil compaction, and crop productivity. Arch Agron Soil Sci 67(5):675–686. https://doi.org/10.1080/03650340.2020.1749267

Moreno F, Murillo JM, Pelegrín F, Girón IF (2006) Long-term impact of conservation tillage on stratification ratio of soil organic carbon and loss of total and active CaCO3. Soil Tillage Res 85(1):86–93. https://doi.org/10.1016/j.still.2004.12.001

Munkholm LJ, Heck RJ, Deen B (2013) Long-term rotation and tillage effects on soil structure and crop yield. Soil Tillage Res 127:85–91. https://doi.org/10.1016/j.still.2012.02.007

Nabel M, Selig C, Gundlach J, von der Decken H, Klein M (2021) Biodiversity in agricultural used soils: threats and options for its conservation in Germany and Europe. Soil Org 93(1):1–11. https://doi.org/10.25674/so93iss1pp1

Obour PB, Lamandé M, Edwards G, Sørensen CG, Munkholm LJ (2017) Predicting soil workability and fragmentation in tillage: a review. Soil Use Manag 33(2):288–298. https://doi.org/10.1111/sum.12340

Olson GW (1981) Archaeology: Lessons on future soil use. J Soil Water Conserv 36(5):261–264. https://www.jswconline.org/content/jswc/36/5/261.full.pdf. Accessed 12 Jan 2022

Peigné J, Ball BC, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? A Review. Soil Use Manag 23(2):129–144. https://doi.org/10.1111/j.1475-2743.2006.00082.x

Peigné J, Vian J-F, Payet V, Saby NPA (2018) Soil fertility after 10 years of conservation tillage in organic farming. Soil Tillage Res 175:194–204. https://doi.org/10.1016/j.still.2017.09.008

Poeplau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops — a meta-analysis. Agric Ecosyst Environ 200:33–41. https://doi.org/10.1016/j.agee.2014.10.024

Pöhlitz J, Rücknagel J, Koblenz B, Schlüter S, Vogel H-J, Christen O (2018) Computed tomography and soil physical measurements of compaction behaviour under strip tillage, mulch tillage and no tillage. Soil Tillage Res 175:205–216. https://doi.org/10.1016/j.still.2017.09.007

Powlson DS, Gregory PJ, Whalley WR, Quinton JN, Hopkins DW, Whitmore AP, Hirsch PR, Goulding KWT (2011) Soil management in relation to sustainable agriculture and ecosystem services. Food Pol 36:S72–S87. https://doi.org/10.1016/j.foodpol.2010.11.025

Prager K, Schuler J, Helming K, Zander P, Ratinger T, Hagedorn K (2011) Soil degradation, farming practices, institutions and policy responses: an analytical framework. Land Degrad Dev 22(1):32–46. https://doi.org/10.1002/ldr.979

Raatz L, Bacchi N, Walzl KP, Glemnitz M, Muller MEH, Joshi J, Scherber C (2019) How much do we really lose?—yield losses in the proximity of natural landscape elements in agricultural landscapes. Ecol Evol 9(13):7838–7848. https://doi.org/10.1002/ece3.5370

Redhead JW, Oliver TH, Woodcock BA, Pywell RF (2020) The influence of landscape composition and configuration on crop yield resilience. J Appl Ecol 57:2180–2190. https://doi.org/10.1111/1365-2664.13722

Ronchi S, Salata S, Arcidiacono A, Piroli E, Montanarella L (2019) Policy instruments for soil protection among the EU member states: a comparative analysis. Land Use Policy 82:763–780. https://doi.org/10.1016/j.landusepol.2019.01.017

Rothstein B, Henneke M, Schröder D (2014) Gesetzliche Instrumente. In: Handbuch der Bodenkunde, pp 1-14. https://doi.org/10.1002/9783527678495.hbbk2005007

Routschek A, Schmidt J, Kreienkamp F (2014) Impact of climate change on soil erosion — a high-resolution projection on catchment scale until 2100 in Saxony/Germany. CATENA 121:99–109. https://doi.org/10.1016/j.catena.2014.04.019

Rübcke von Veltheim F, Heise H (2020) The AgTech startup perspective to farmers ex ante acceptance process of autonomous field robots. Sustainability 12(24):10570. https://doi.org/10.3390/su122410570

Rübcke von Veltheim F, Heise H (2021) German farmers' attitudes on adopting autonomous field robots: an empirical survey. Agric 11 (3):216. https://www.mdpi.com/2077-0472/11/3/216

Sanchez JE, Harwood RR, Willson TC, Kizilkaya K, Smeenk J, Parker E, Paul EA, Knezek BD, Robertson GP (2004) Managing soil carbon and nitrogen for productivity and environmental quality. Agron J 96(3):1. https://doi.org/10.2134/agronj2004.0769

Sattler C, Nagel UJ (2010) Factors affecting farmers' acceptance of conservation measures—a case study from north-eastern Germany. Land Use Policy 27(1):70–77. https://doi.org/10.1016/j.landusepol.2008.02.002

Savić B, Evgrafova A, Donmez C, Vasić F, Glemnitz M, Paul C (2021) Assessing the role of kettle holes for providing and connecting amphibian habitats in agricultural landscapes. Land 10(7):692. https://doi.org/10.3390/land10070692

Scheffler M, Wiegmann K (2019) Quantifizierung von Maßnahmenvorschlägen der deutschen Zivilgesellschaft zu THG - Minderungspotenzialen in der Landwirtschaft bis 2030 [Kurzstudie im Auftrag der Klima-Allianz Deutschland]. Öko-Institut e.V

Schlüter S, Großmann C, Diel J, Wu G-M, Tischer S, Deubel A, Rücknagel J (2018) Long-term effects of conventional and reduced tillage on soil structure, soil ecological and soil hydraulic properties. Geoderma 332:10–19. https://doi.org/10.1016/j.geoderma.2018.07.001

Scholz C, Möller K, Ruckelshausen A, Hinck S, Göttinger M (2014) Automatic soil penetrometer measurements and gis-based documentation with the autonomous field robot platform bonirob. 12th International Conference on Precision Agriculture, Sacramento, CA

Schulte RPO, Creamer RE, Donnellan T, Farrelly N, Fealy R, O'Donoghue C, O'hUallachain D (2014) Functional land management: a framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environ Sci Policy 38:45-58. https://doi.org/10.1016/j.envsci.2013.10.002

Seehusen T, Riggert R, Fleige H, Horn R, Riley H (2019) Soil compaction and stress propagation after different wheeling intensities on a silt soil in South-East Norway. Acta Agriculturae Scandinavica, Section B - Soil Plant Sci 69(4):343–355. https://doi.org/10.1080/09064710.2019.1576762

Seitz S, Goebes P, Puerta VL, Pereira EIP, Wittwer R, Six J, van der Heijden MGA, Scholten T (2018) Conservation tillage and organic farming reduce soil erosion. Agron Sustain Dev 39(1):4. https://doi.org/10.1007/s13593-018-0545-z

Sharratt B, Voorhees W, McIntosh G, Lemme G (1998) Persistence of soil structural modifications along a historic wagon trail. Soil Sci Soc Am J 62(3):774–777. https://doi.org/10.2136/sssaj1998.03615995006200030033x

Sieusoil (2020) Revision of the "thematic strategy for soil protection". https://www.sieusoil.eu/thematic-strategy-for-soil-protection-revision/. Accessed 17 Sep 2021

Snyder BF (2020) The genetic and cultural evolution of unsustainability. Sustain Sci 15(4):1087–1099. https://doi.org/10.1007/s11625-020-00803-z

Steingröver EG, Geertsema W, van Wingerden WKRE (2010) Designing agricultural landscapes for natural pest control: a transdisciplinary approach in the Hoeksche Waard (The Netherlands). Landsc Ecol 25(6):825–838. https://doi.org/10.1007/s10980-010-9489-7

Steinmann H-H, Dobers ES (2013) Spatio-temporal analysis of crop rotations and crop sequence patterns in Northern Germany: potential implications on plant health and crop protection. J Plant Dis Prot 120(2):85–94. https://doi.org/10.1007/BF03356458

Tamburini G, Bommarco R, Wanger TC, Kremen C, van der Heijden MGA, Liebman M, Hallin S (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv 6 (45):eaba1715. doi:https://doi.org/10.1126/sciadv.aba1715

Tarpani RRZ, Alfonsín C, Hospido A, Azapagic A (2020) Life cycle environmental impacts of sewage sludge treatment methods for resource recovery considering ecotoxicity of heavy metals and pharmaceutical and personal care products. J Environ Manag 260:109643. https://doi.org/10.1016/j.jenvman.2019.109643

Techen A-K, Helming K (2017) Pressures on soil functions from soil management in Germany. A Foresight Review. Agron Sustain Dev 37(6):64. https://doi.org/10.1007/s13593-017-0473-3

ten Damme L, Stettler M, Pinet F, Vervaet P, Keller T, Munkholm LJ, Lamandé M (2019) The contribution of tyre evolution to the reduction of soil compaction risks. Soil Tillage Res 194:104283. https://doi.org/10.1016/j.still.2019.05.029

Thorsøe MH, Noe EB, Lamandé M, Frelih-Larsen A, Kjeldsen C, Zandersen M, Schjønning P (2019) Sustainable soil management — farmers' perspectives on subsoil compaction and the opportunities and barriers for intervention. Land Use Policy 86:427–437. https://doi.org/10.1016/j.landusepol.2019.05.017

Tickell J, Tickell RH (2020) Kiss the Ground [Documentary]. BPR Benenson Productions, The Redford Center, Netflix. https://kisstheground.com/film/. Accessed 12 Jan 2022

Tiemann LK, Grandy AS, Atkinson EE, Marin-Spiotta E, McDaniel MD (2015) Crop rotational diversity enhances belowground communities and functions in an agroecosystem. Ecol Lett 18(8):761–771. https://doi.org/10.1111/ele.12453

Tur-Cardona J, Bonnichsen O, Speelman S, Verspecht A, Carpentier L, Debruyne L, Marchand F, Jacobsen BH, Buysse J (2018) Farmers' reasons to accept bio-based fertilizers: a choice experiment in seven different European countries. J Clean Prod 197:406–416. https://doi.org/10.1016/j.jclepro.2018.06.172

Uhlig M (2019) Unser Boden, unser Erbe [Documentary]. Tisda Media, MovieBiz Films, Lighthouse Home Entertainment, W-film. https://www.wfilm.de/unser-boden-unser-erbe/. Accessed 12 Jan 2022

van Capelle C, Schrader S, Brunotte J (2012) Tillage-induced changes in the functional diversity of soil biota — a review with a focus on German data. Eur J Soil Biol 50:165–181. https://doi.org/10.1016/j.ejsobi.2012.02.005

van den Akker JJH, Soane B (2005) Compaction. In: Hillel D (ed), Encyclopedia of soils in the environment. Elsevier, pp 285-293. https://doi.org/10.1016/B0-12-348530-4/00248-4

van den Berge S, Baeten L, Vanhellemont M, Ampoorter E, Proesmans W, Eeraerts M, Hermy M, Smagghe G, Vermeulen I, Verheyen K (2018) Species diversity, pollinator resource value and edibility potential of woody networks in the countryside in northern Belgium. Agric Ecosyst Environ 259:119–126. https://doi.org/10.1016/j.agee.2018.03.008

van Vooren L, Reubens B, Broekx S, de Frenne P, Nelissen V, Pardon P, Verheyen K (2017) Ecosystem service delivery of agri-environment measures: a synthesis for hedgerows and grass strips on arable land. Agric Ecosyst Environ 244:32–51. https://doi.org/10.1016/j.agee.2017.04.015

Vida C, de Vicente A, Cazorla FM (2020) The role of organic amendments to soil for crop protection: Induction of suppression of soilborne pathogens. Ann Appl Biol 176(1):1–15. https://doi.org/10.1111/aab.12555

Virto I, Imaz MJ, Fernández-Ugalde O, Gartzia-Bengoetxea N, Enrique A, Bescansa P (2015) Soil degradation and soil quality in Western Europe: current situation and future perspectives. Sustainability 7(1):313–365. https://doi.org/10.3390/su7010313

Volk L, Denker S, Rose S (2011) How to increase diesel fuel efficiency in agriculture. Landtechnik 2:140–143

Wagg C, Bender SF, Widmer F, van der Heijden MGA (2014) Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proc Natl Acad Sci USA 111(14):5266–5270. https://doi.org/10.1073/pnas.1320054111

Werner M, Wauters E, Bijttebier J, Steinmann H-H, Ruysschaert G, Knierim A (2017) Farm level implementation of soil conservation measures: farmers' beliefs and intentions. Renew Agric Food Syst 32(6):524–537. https://doi.org/10.1017/S1742170516000454

Wezel A, Casagrande M, Celette F, Vian J-F, Ferrer A, Peigné J (2014) Agroecological practices for sustainable agriculture. A Review. Agron Sustain Dev 34(1):1–20. https://doi.org/10.1007/s13593-013-0180-7

Wojewoda D, Russel S (2003) The impact of a shelterbelt on soil properties and microbial activity in an adjacent crop field. Pol J Ecol 51(3):291–307

Wuepper D, Wimmer S, Sauer J (2020) Is small family farming more environmentally sustainable? Evidence from a spatial regression discontinuity design in Germany. Land Use Policy 90:104360. https://doi.org/10.1016/j.landusepol.2019.104360

Wunder S, Bodle R (2019) Achieving land degradation neutrality in Germany: implementation process and design of a land use change based indicator. Environ Sci Policy 92:46–55. https://doi.org/10.1016/j.envsci.2018.09.022

Zaller JG, Heigl F, Ruess L, Grabmaier A (2014) Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. Sci Rep 4(1):5634. https://doi.org/10.1038/srep05634

Zinngrebe Y, Pe'er G, Schueler S, Schmitt J, Schmidt J, Lakner S (2017) The EU's ecological focus areas — how experts explain farmers' choices in Germany. Land Use Policy 65:93-108. https://doi.org/10.1016/j.landusepol.2017.03.027