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REVIEW ARTICLE

# Pressures on soil functions from soil management in Germany. A foresight review

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## Abstract

Global trends in demand for biomass-based food, feed, energy, and fiber call for a sustainable intensification of agricultural production. From the perspective of sustaining soil functions, this implies the integration of soil productivity with the other soil functions and services, namely carbon sequestration, water purification and retention, and nutrient and matter cycling as well as biodiversity. Soil management is the key to this integration. The proper anticipation of future opportunities and challenges for sustainable soil management requires an analysis of drivers and trends affecting soil management. Here, we review drivers and trends of soil management and their relevance for soil functions taking Germany as an example of industrialized agricultural systems with low yield gaps. We analyzed socio-economic, biophysical and technological drivers and identified two types of future management changes: (1) Quantitative changes, i.e., more or less of the same input factors, such as fertilizers, as part of a moderate intensification. (2) Qualitative changes: There, we found the strongest signals for the following practices: higher precision and lightweight machines triggered by information and communication technology (ICT) and robotics; diversification of crop rotations, including the integration of lignocellulosic crops; inoculation with biota; and new crop varieties. Positive practices may be reinforced by a behavioral trend towards sustainable soil management, driven by increasing awareness, knowledge, and consumer demand. They offer opportunities for relieving mechanical pressures from weight and contact stress, chemical pressures from pesticides and fertilizers and promoting soil biodiversity without compromising the soil's production function. We also found threats, such as increased removal of organic residues and potentially harmful organisms. This foresight study is the first to delineate opportunities and challenges for sustainable soil management and intensification. It informs researchers who intend to improve the knowledge base for reinforcement of positive and mitigation of negative trends of soil management.

**Keywords** Foresight · Soil management · Sustainable intensification · Drivers of agronomic trends · Cropping systems

**Contents**

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## 1 Introduction

The sustainable management of agricultural soils is a global concern. Soils are the basis for producing the greatest quantity of food and feed and contribute an increasing share of biomass for energetic and industrial purposes. Agricultural soils also fulfill fundamental functions for ecosystem services, such as water and nutrient regulation and carbon storage, and they contribute essentially to biodiversity. But at the same time, soil functions are threatened by degradation processes, and approximately one quarter of global cropland may already be degrading due to human pressures (Le et al. 2016).

While intensive agriculture is generally associated with promoting soil degradation, the reality is more complex (FAO and ITPS 2015). The occurrence and rate of soil degradation depend on the combination of soil management decisions and their interrelations with local geo-biophysical, socio-economic, and climatic conditions. The terms “sustainable intensification” (Garnett et al. 2013) and “ecological intensification” (Tittonell 2014) initiated the challenge for agricultural management to increase the production while minimizing the resource use, intensifying ecological interaction, exploiting the inherent capacity of the soils to produce, and maintaining all other soil functions and ecosystem services. This indicates that the multifunctionality of soils (Schulte et al. 2014) must be managed and improved.

Taking appropriate actions for sustainable intensification requires the analysis of drivers of soil management and the challenges and opportunities they entail. This is especially true for research; being an important driver, it has the potential to reinforce positive and mitigate negative developments regarding soil management. As research often takes many years before the results may become applicable in the field (Colinet et al. 2014, similar Alston et al. 2008), foresight on the drivers of soil management is important to inform research directions.

For Europe, a number of foresight studies on agriculture exist. Important examples include Last et al. (2015) with a foresight study on the Swiss food system, Teagasc (2016) on the Irish agri-food sector, and Foresight (2011) and Alexandratos and Bruinsma (2012) on the future of food and farming on a global scale. Schindler et al. (2014) and EU SCAR (2016) addressed information and communication technologies (ICT) and robotics in European agriculture in their broader foresight studies. Other types of studies, such as forecasts and projections (cited in Section 3.1), address the demand side of products from agricultural soils. None of these studies directly addresses soil management, but together, they anticipate an intensification of agricultural production at the global level, which poses threats to soil functions. But the studies also imply opportunities for improved soil management. However, to date, no foresight or similar study has focused directly and comprehensively on the management of agricultural soils. Nevertheless, soil management is the key pressure shaping soil multifunctionality.

This paper presents a review of the drivers of soil management for the exemplary case of Germany as one of the highly industrialized countries with very low yield gaps. The aim was to analyze the existing evidence of emerging trends in soil management practices (Fig. 1) and to identify upcoming and future opportunities and challenges for soil functions that are relevant to be addressed, among others, in experimental research and scenario modeling. This study was conducted in

**Fig. 1** Technological development is a key driver of change in soil management. The example is one of the first agricultural robots being close to commercialization, which are small and lightweight, so that they can reduce weight and contact stresses and facilitate smaller-scaled field patterns. As its main task, this robot can make weed control much more efficient. It identifies the weeds with a sensor and sprays each plant individually. The developers are also working on an implement for organic farming. (photo credits: Ecorobotix autonomous robot weeder, 2016)

the frame of the German research program “BonaRes—soil as a sustainable resource for the bioeconomy” (www.bonares.de/en/) to inform research and modeling activities. Its implications are also relevant for the wider research community.

## 2 Materials and methods

### 2.1 Analytical framework

The conceptual starting point of the analysis was the DPSIR (Driver-Pressure-State-Impact-Response) framework introduced by the European Environment Agency (Smeets and Weterings 1999). “Drivers” are defined as social, economic, or environmental developments that lead to “pressures” being exerted on the environment (Tscherning et al. 2012). In our case, “pressures” are exerted by soil management leading to changes in the “states” of soils regarding their processes and functions. These changes, in turn, lead to different social, economic, or environmental “impacts,” such as climate change mitigation, and may lead to different societal “responses,” e.g., mitigation policies. It is important to note that “pressure” in this context is not necessarily connected to negative outcomes but to any activity that causes changes in soil functions, negatively or positively.

The analytical framework of this study (Fig. 2) builds upon the DPS part of DPSIR. We identified the type of soil management changes (pressures) that may emerge in response to the identified drivers. The drivers were clustered into socio-economic, biophysical, and technological categories. Drivers acted upon pressures (soil management) in two ways, quantitatively and qualitatively:

1) Quantitative changes affect soil management in terms of decreased or increased biomass production. Ceteris paribus, the quantities of production factors are changed, e.g., adding less/more of the same fertilizer with the same application technology as before.
2) Qualitative changes affect specific aspects of soil management qualitatively, for example, by making the crop rotation more diverse.

We reviewed whether such soil management categories affect soil functions. We refer to the five key soil functions relevant to agricultural soils: (1) the production of food, fiber, and biofuel; (2) water purification and retention; (3) carbon sequestration; (4) habitat for biodiversity; and (5) recycling of nutrients and (agro)chemicals (Schulte et al. 2014, complemented by the item water retention). For quantitative changes (Section 3), we contrasted the extensification and intensification of the production with intensification prioritizing the production function of soils and thus potentially threatening other soil functions. For qualitative changes (Section 4), we

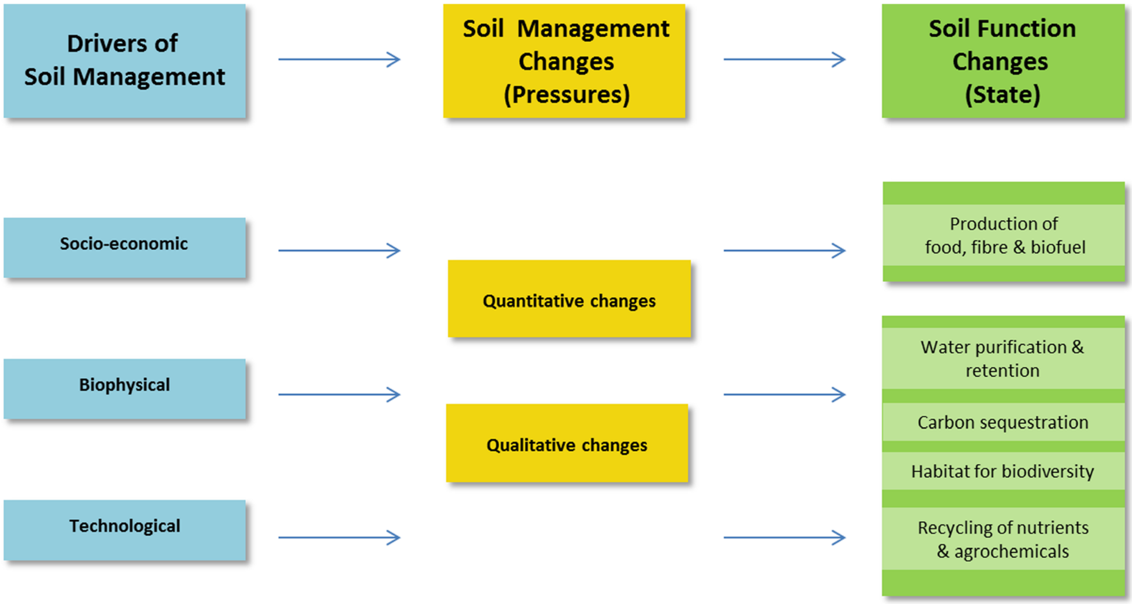

**Fig. 2** Analytical framework: Drivers of soil management trigger quantitative and/or qualitative changes in soil management (pressure). Quantitative changes refer to in-/extensification without qualitative changes in the system (more or less of the same input factors such as fertilizers). The changed soil management may lead to changes in soil functions (state)

contrasted improving and threatening influences on soil functions.

## 2.2 Literature and document analysis

The material analysis was conducted between January and November 2016 and included a total of 267 sources that were analyzed in the following three steps:

1) The first step was to analyze existing foresight studies, projections, and forecasts for their relevance for agricultural soil management. In this process, we identified drivers of soil management, how they are developing and how they affect soil management. This analysis was based on scientific literature. We preferred peer-reviewed meta-studies and systematic reviews over peer-reviewed reviews over peer-reviewed research studies over gray literature (Table 1). The latter was also included in the analysis because foresight studies have mostly been published as such and not as peer-reviewed literature. The literature search was initially performed with Google Scholar and Web of Science. Because Google Scholar returned more useful results, this search engine was ultimately used.
2) The second step was to identify further drivers of agricultural soil management beyond the future-oriented literature. Important examples are studies that identify correlations between farmers' attributes and soil conservation behavior and studies that identify correlations between exogenous factors such as dietary changes and global land use changes. This step was fundamental, as documents analyzed in step one addressed agricultural production in general, but none addressed soil management in particular. The literature search followed the same process as step one.
3) The third step was to assess what role the drivers of agricultural soil management, identified in steps one and two, play in Germany, i.e., what the characteristics of drivers in Germany are, and what kind of changes in soil management they may lead to. Sources included scientific evidence, governmental sources, and other sources (Table 1). Governmental sources were used to analyze, if available, statistics and forecasts of some drivers, for example, the changes in farmers' attributes such as age and education. For public debate on a driver or pressure, the three most relevant German magazines for this analysis (Top Agrar, DLG-Mitteilungen, Agra-Europe), directed at different stakeholder groups, were sighted and selected according to the analytics of the readers of several magazines (Schleyerbach 2009), their own descriptions of their target groups (DLG-Mitteilungen 2016; Agra-Europe 2016e), and the authors' experiences. Other online information for different stakeholders was taken into account to analyze either the public debate (e.g., a statement of an important lobby group) or to analyze the market and industry trends when there was no current scientific analysis available.

Most sources were analyzed qualitatively with a mixture of an inductive and a deductive approach. For example, the process started out with some knowledge and ideas of drivers. So we looked for evidence of those drivers but also openly for additional drivers. We extended or rearranged our categorization (Fig. 3) of drivers when finding new drivers. Some official statistics were evaluated quantitatively by, for example, calculating percentages of farmers' attributes in clusters of age.

The approach was influenced by the fact that there is very little literature available that specifically addresses

**Table 1** Sources of the analyzed material and hierarchy of their selection

| Type | Analytical topics | Hierarchical level | Sources |
|---|---|---|---|
| Scientific evidence | Foresight reviews, identification of drivers, specification of drivers, public debate, technological development | 1 | Peer-reviewed meta-studies/systematic reviews |
| | | 2 | Peer-reviewed other reviews |
| | | 3 | Peer-reviewed research articles |
| | | 4 | Gray literature |
| Governmental sources (national and international) | Specification of drivers | 1 | Official statistics |
| | | 1 | Laws and legally binding commitments/treaties |
| | | 2 | Not legally binding strategies/goals and associated communications |
| Other sources | Public debate, technological development | 1 | Agricultural magazines |
| | | 1 | Online information on different stakeholders |

the drivers of soil management. The exception is literature on the adoption of conservation behavior, but this is only a small part in this overall analysis. This is one reason why the study had to be explorative, taking very broad and diverse material into account. Also, the foresight character of the study made it necessary to capture media discussion and to view sources that have not yet been scientifically analyzed or been published in peer-reviewed articles.

Important to note is that prices of agricultural products and market dynamics are, with exceptions, not regarded as the main drivers. Prices are in the medium and long term mainly a translation of the increased or decreased demand for products into financial terms, while the demand in terms of the amount of biomass is the driver of interest here. Several studies, cited in Section 3, have assessed the commodity demand with economic models; thus, market dynamics underlie some of the results.

## 3 Quantitative changes in pressures on soil functions

A complex net of the drivers and trends of soil management was identified, shown simplified in Fig. 3. Drivers evoking quantitative changes in soil management (intensification and/or extensification by using more or less of the same inputs in the same manner) are listed in Table 2 and further outlined with short narratives in this section. Ceteris paribus, intensification, i.e., producing more biomass from the same land, is connected to higher nutrient, pesticide, and water input and higher harvest frequencies (FAO and ITPS 2015: 60ff.).

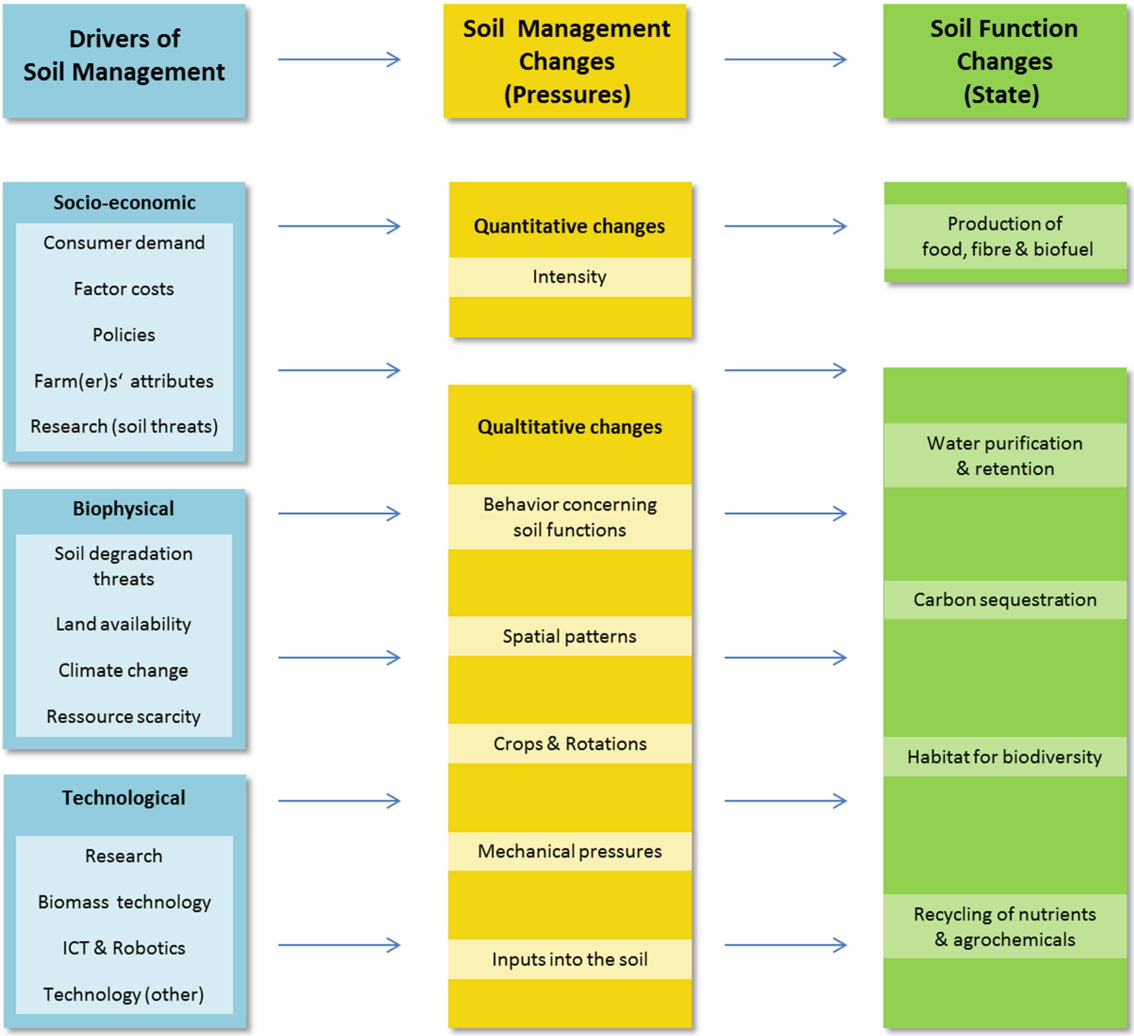

**Fig. 3** Overview of the identified drivers of soil management, categories of soil management (pressures) changes, and soil functions (state) that are affected by soil management. Socio-economic, biophysical, and technological drivers affect soil management in terms of changing intensity (quantitative changes) and in five categories of qualitative changes. The pressures together affect soil processes, which in turn affect the interaction between the soil productivity function and the other soil functions

**Table 2** Drivers and trends of quantitative pressures on soil functions (intensity of soil management) at the global level and for Germany

| Driver | Direction | Sources |
|---|---|---|
| Global | | |
| Consumer demand: | | |
| Increasing demand for food for more people and per capita | ↑ | United Nations 2015; FAO 2015a; FAO 2013a; Godfray and Robinson 2015; Foresight 2011; Tilman et al. 2011; Valin et al. 2014; Alexander et al. 2015; Kastner et al. 2012 |
| Increasing demand for animal products per capita | ↑ | |
| Potential mitigation of increase in demand for animal products per capita | ↓ | |
| Increasing demand for biomass for bioenergy | ↑ | IEA 2015: 154; IEA 2012 in Popp et al. 2014; UNFCCC Secretariat 2015; REN21 2015; European Commission 2014; REN21 2013; EU Renewable Energy Directive (2009/28/EC); Fuel Quality Directive (2009/30/EC); Erneuerbare-Energien-Gesetz (EEG); Laggner et al. 2014; Vollprecht et al. 2015; Bundesministerium für Ernährung und Landwirtschaft 2014; Commission 2012; Alexander et al. 2015; Foresight 2011 |
| Increasing food losses and waste | ↑ | Gustavsson et al. 2011; FAO 2013b; Alexander et al. 2015 |
| Potential mitigation of food losses and waste | ↓ | FAO 2016a; Chalak et al. 2016; European Commission 2015a; European Commission 2011; General Assembly 2015 |
| Consumer demand/biomass technology: potentially decreasing demand for biomass for bioenergy because of technological breakthroughs such as the integration of wind and solar solutions in urban structures | ↓ | Foresight 2011; Kolokotsa 2017 |
| Increasing industrial use of biomass | ↑ | Albrecht and Ettling 2014; Morrison and Golden 2015; OECD 2009; Institute for Bioplastics and Biocomposites et al. 2015; European Bioplastics 2015 |
| Soil degradation threats: | | |
| Decreased soil production capacity of some soils (including climate change impact) | ↑ | FAO and ITPS 2015; Bai et al. 2008; Le et al. 2016; IPCC 2014 |
| Land availability: | | |
| Decreased land availability | ↑ | Gardi et al. 2015; Smith et al. 2016; Lambin et al. 2013; Watson et al. 2014; Alexandratos and Bruinsma 2012 |
| No significant conversion of land to cropland | → | FAO 2013a; Hansen et al. 2013; Foley et al. 2011; Garnett et al. 2013; FAO and ITPS 2015; Ray et al. 2013; Laurance et al. 2014 |
| Converting land to cropland | ↓ | Alexandratos and Bruinsma 2012 |
| Technology: | | |
| Yield stagnation | ↑ | Wiesmeier et al. 2015; Ray et al. 2012 |
| Closing yield gaps (and reallocating production) | ↓ | Alexander et al. 2015; Kastner et al. 2012; Foley et al. 2011; Mauser et al. 2015 |
| Overall globally | ↑ to ↗ | |
| Germany | | |
| Factor costs: | | |
| Relatively low marginal utilities of inputs (price relations plus low yield gaps and yield stagnation) | → | van Grinsven et al. 2015; Mauser et al. 2015; Wiesmeier et al. 2015; European Commission 2015b |
| Climate change: Narrower crop rotations (including double cropping) in some regions in the long term | ↑ | Nendel et al. 2014; Troost and Berger 2015; Gutzler et al. 2015; Peters and Gerowitt 2014 |
| Policies: | | |
| Towards extensification | ↓ | Isermeyer 2014; Bundesministerium für Ernährung und Landwirtschaft 2015b; Popp et al. 2015; Erjavec and Erjavec 2015; Wissenschaftlicher Beirat für Agrarpolitik beim BMELV 2010; Agra-Europe 2016b; Deutsche Bundesregierung 2016 |
| Overall Germany | ↗ to → | |

"↑" indicates intensification, and "↓" indicates extensification relative to the intensification trend

Drivers were analyzed at the global and national levels because, in a world of globalized trade, the worldwide demand for agricultural products is relevant for overall production intensities, while national characteristics shape the national reactions to global drivers, i.e., the translation into soil management.

The need for intensification is often asserted by different stakeholders simply due to the growing world population. Many studies have attempted to assess the growing demand for agricultural products. In particular, the studies aiming to quantify future demand are faced with having to make simplifications, such as considering only the most obvious and strong drivers, making assumptions about selected factors or using selected model approaches. In contrast, we abstained from quantification in favor of drawing a multifaceted picture of the drivers.

Globally, current projections of food demand suggest a massive increase derived from population growth and changing diets towards more animal products, which require more inputs from cropland and grassland per calorie than plant products. Changing diets may even surpass the driver of increasing calorie needs (Alexander et al. 2015, Kastner et al. 2012). These two drivers are the greatest in terms of quantitative changes. For example, Godfray and Robinson (2015) found that a range of different studies suggests increases in food demand from approximately 2010 to 2050 of between 50 and 100%, involving a high degree of uncertainty. It is possible that developing countries will start campaigning for healthy diets earlier in their development stages than industrial countries, seeing for example how improving diets and promoting sustainable lifestyles is a global endeavor with the Sustainable Development Goals (United Nations 2015). The digitalization of the world may support this by passing over health and animal welfare trends to parts of the developing world via non-governmental channels. Biomass demand for energy is projected to increase over the long term. At the same time, other energy sources and ways to use solar and wind energy more effectively are likely to be developed, thereby mitigating the increasing demand for biomass-based energy. Demand for biomass for industrial purposes is still low, but some segments grow fast. If the bioeconomy strategies in place in many countries move the trend forward, this is likely to significantly increase biomass demand. Food losses and waste are accounting for the production on approximately one third of agricultural land (FAO 2013b). This proportion may increase with the increased adoption of “Western lifestyles,” but there are movements and policies aiming to reduce food waste; thus, there may be waste reductions that relieve the pressure on agricultural soils. Closing yield gaps means, on the one hand, that production is intensified in some parts of the world. On the other hand, in places in which this intensification starts from a very low level, it must not be associated with soil degradation, but it may be more relevant that it relieves pressure on soils elsewhere. Still, pressure on soils is also likely to increase because less land will be available due to competing land uses, and some land will have reduced production capacities due to soil degradation, climate change, or other factors accounting for yield stagnation. These reduced capacities will place more pressure on the rest of the agricultural soils. There are varying assessments of how much land could be additionally converted to agricultural soils. However, there is convincing evidence that this area is not large, and such conversion should generally be avoided due to negative environmental outcomes.

Overall, it seems that a strong force to increase the production on agricultural land is occurring globally, with only little indication that policymakers and civil societies will succeed to relax biomass demand by addressing, for example, food losses and nutrition habits.

Whether and how this demand to produce more biomass is realized is differentiated locally. Europe on the whole, and Germany in particular, have very low yield gaps (van Grinsven et al. 2015), and thus, very low potential biomass production increases (Mauser et al. 2015: 4) compared to many other world regions. Because of the low yield gap and the yield stagnation in Central and Northern European countries (Wiesmeier et al. 2015), marginal utilities of additional inputs are much lower than in other areas of the world, so the economic incentives to intensify are low. Price relations between inputs and outputs are expected to decrease between 2015 and 2025 in the EU despite increased demand for agricultural products due to higher resource prices (European Commission 2015b). In addition, European agricultural policies include measures promoting extensification (agri-environmental measures, “greening” of the Common Agricultural Policy (CAP) of the EU). Such policies have a mildly increasing trend, which may continue for the foreseeable future (see Section 4.1). In conclusion, for Europe and particularly for Germany, one of the countries with the most industrialized and intensive agriculture, the trends for intensification may have less strength than in many other parts of the world, at least in the coming years. In the long term, the further promotion of the bioeconomy and the longer vegetation periods (climate change) may reinforce the trend towards intensification after all.

## 4 Qualitative changes in pressures on soil functions (changes in soil management)

This section is organized according to the categories of soil management that were identified as being affected by drivers and trends. Five categories of soil management pressures can be differentiated: (i) general behavior concerning soil functions, (ii) spatial patterns, (iii) crops and rotations, (iv) mechanical pressures, and (v) inputs into the soil (Fig. 3). The last three categories are in line with what Haddaway et al. (2015) identified as relevant soil management pressures leading to different soil organic carbon (SOC) contents of soil (crop rotations, tillage, amendments, and nitrogen fertilizer). "Spatial patterns" were identified as another category, as they are important for some soil functions (biodiversity), and they affect soil degradation processes such as soil erosion. This category supports the argument of Duru et al. (2015) regarding the importance of the spatial organization of cropping systems for ensuring the delivery and resilience of ecosystem services. The first category was identified as an explicit superordinate category because some drivers trigger changes in that direction irrespective of the specific measures taken. Drivers affecting qualitative changes to soil management are listed in the tables together with their sources from the literature, and an indication of whether these trends are expected to increase or decrease soil multifunctionality is included. Short narratives on the more complex interrelationships are given in the subsections; drivers are written in bold italics.

## 4.1 Behavior concerning soil functions

There are drivers that generally influence whether the soil is managed in favor of maintaining soil functions (Table 3). This means that these drivers motivate or enable farmers to consider taking actions to maintain soil functions in general (often referred to as "conservation behavior") or to neglect it. Which specific soil management practices are considered is subject to different circumstances.

**Table 3** Drivers and trends of behavioral aspects concerning soil functions in Germany

| Drivers | Direction | Sources |
|---|---|---|
| Behavior concerning soil functions | | |
| *Consumer demand*: trends towards more (perceived) environmentally friendly (organic, local, non-GMO) products, traceability, and transparency | ↑ | Hempel and Hamm 2016; Bund Ökologische Lebensmittelwirtschaft 2012, 2016; Emberger-Klein et al. 2016; Schindler et al. 2014; Teagasc 2016; Last et al. 2015 |
| *Policies*: weak trend towards more environmentally friendly agricultural production (and with *ICT*, more opportunities for soil management schemes) | ↑ | Glæsner et al. 2014; European Commission 2013; Isermeyer 2014; Popp et al. 2015; Erjavec and Erjavec 2015; Hogan 2016; Agra-Europe 2016b; Wissenschaftlicher Beirat für Agrarpolitik beim BMELV 2010; Deutsche Bundesregierung 2016; Teagasc 2016; United Nations 2015; FAO 1982, 2015b; Montanarella 2015; Bundesministerium für Ernährung und Landwirtschaft 2015b; Pe'er et al. 2016; Zander et al. 2016b; Anon 2016 and more specific policies in the subsections; Agra-Europe 2017; Vrebos et al. 2017 |
| *Attributes of farm(er)s*: most important: change in farmers' age structure and younger farmers are better educated and more accepting of *ICT* | ↑ | Gray et al. 2000; Werner et al. 2014; Wauters et al. 2010; Prager and Curfs 2016; Norris and Batie 1987; Techen et al. 2015; Lynne et al. 1988; Smit and Smithers 1992; Baumgart-Getz et al. 2012; Odening et al. 2016; Bundesministerium für Ernährung und Landwirtschaft 2015a; European Commission 2015b; Offermann et al. 2016; Parker et al. 2007; Soule et al. 2000; Sklenicka et al. 2015; Fraser 2004; Statistisches Bundesamt 2014a; Kay et al. 2015; Herre 2013; Techen 2015; Prokopy et al. 2008; Statistisches Bundesamt 2014b; Statistisches Bundesamt 2011; Gindele et al. 2015; Agra-Europe 2016c |
| *Soil degradation threats*, together with more information *(ICT)* and improved knowledge *(research)*, may drive soil sensitive behavior, partially via *policies* pertaining to soil degradation threats | ↑ | Jones et al. 2012; European Commission 2002; Marahrens et al. 2015; Techen 2015; Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2007; Stone et al. 2016; Orgiazzi et al. 2016; Thiele-Bruhn et al. 2012; Postma-Blaauw et al. 2010; Tsiafouli et al. 2015; Clermont-Dauphin et al. 2014; Teagasc 2016; Deutsche Bundesregierung 2016; Griffiths et al. 2016; COP to the CBD 2010a, b |
| *Climate change*, together with *policies*, drives mitigation and adaptation measures, which concern several soil management categories described in subsequent sections | ↑ | Buth et al. 2015; Gömann et al. 2015; Ministère de l'Agriculture 2015/2016; Deutsche Bundesregierung 2016; Wissenschaftlicher Beirat Agrarpolitik et al. 2016; Paris Agreement 2015 |
| *Technology (ICT)* improves traceability, transparency and information on soil management impacts | ↑ | Fountas et al. 2015a; Teagasc 2016 |

"↑" indicates management likely being beneficial to soil multifunctionality. "↓" indicates management likely being threatening to soil multifunctionality. "?" indicates that no clear trend could be detected. Data in italics: drivers identified to affect soil management and soil functional changes

***Consumer demand*** in Germany and other European countries has trended towards increasing awareness of environmental issues of food production (Table 3). This change is reflected in the increasing demand for organic (Bund Ökologische Lebensmittelwirtschaft 2012, 2016) and local food products (Hempel and Hamm 2016) and the sustained resistance against genetically modified organisms (Emberger-Klein et al. 2016). Foresight studies predict that this trend and the demand for more diverse and specialized food as well as for the traceability and transparency in production will persist (Schindler et al. 2014; Teagasc 2016; Last et al. 2015). At the same time, new ***information and communication technologies*** will enable more traceability and information on the impacts of soil management on soil functions. This may feed back towards more explicit demands from consumers. Fountas et al. (2015a) found that emerging farm management information systems may become commercialized in the coming decades that respond to the increasing demand for environmental integration. This improves the technical basis for certification schemes that include aspects of soil management. As a consequence, improved soil management schemes are expected in the future by Teagasc (2016: 63).

Soil management schemes may be realized as part of the Common Agricultural Policy of the European Union (***policies***) (Table 3), which already includes regulations and funding measures with relevance to soil management. A further "greening" of the CAP is to be expected but with unclear impact. At the European level, better soil governance is not directly underway after the proposal for the Soil Framework Directive failed in 2014. However, soil protection is still a goal of the EU (European Commission 2013), and there are a number of EU policy instruments relevant for soils (Vrebos et al. 2017; Glæsner et al. 2014). Prominently, under pressure of the European Commission, the German government improved the implementation of the Nitrates Directive in 2017 by amending the fertilization law (Agra-Europe 2017)—a several-year-long process showing that policy is going into the direction of protecting natural resources, but with a strong opposing lobby. For Germany, some signals of a movement towards sustainable soil management are evident at national and international policy levels. Most prominently, the UN 2030 Agenda with its Sustainable Development Goals (SDGs) has recently given greater political attention to sustainable soil use (United Nations 2015). The SDGs have been integrated into the German sustainability strategy (Deutsche Bundesregierung 2017) that now acknowledges a stronger role of soils than before (Deutsche Bundesregierung 2002). With the first and revised World Soil Charter, all members of the FAO endorsed the aim to manage soils sustainably, along with some principles and guidelines for action (FAO 1982, 2015b). However, its uptake in concrete policy action remains uncertain (Montanarella 2015: 33). In the sections about climate change and biodiversity loss, more relevant policies are mentioned in association with more specific soil management categories.

There are some attributes of farms and farmers (***farm(er)s' attributes***) that have been identified as influencing the acknowledgment of soil functions in soil management (Table 3). For Germany, a trend towards a higher education level of farmers, together with the age structure, seems to be the strongest identifiable trend of farms' and farmers' characteristics that, together with technological advancements, may lead to an improved consideration of soil multifunctionality. The role of tenure issues, such as whether farmers manage own or rented land, is not well investigated in the German context. These issues may be relevant especially because of the trend in some regions for large farms to be built up by (domestic or foreign) financial investors with weak or short-term bonds to the land.

***Soil degradation threats*** may also drive farmers towards an improved recognition of soil multifunctionality (Table 3). This may be triggered by improved knowledge and information about the extent of soil erosion, compaction, organic matter decline, and soil biodiversity loss and its feedback on yields at specific sites (***research***, ***ICT***) (Table 3). Especially in the field of soil biodiversity, new insights from research and monitoring are to be expected (Griffiths et al. 2016; Stone et al. 2016).

***Climate change*** (Buth et al. 2015; Gömann et al. 2015) directly drives adaptation to higher temperatures, longer vegetation periods, and more extreme weather events, while mitigation measures, e.g., carbon sequestration, are primarily driven by policies (Paris Agreement 2015; Deutsche Bundesregierung 2016; Bundesministerium für Ernährung und Landwirtschaft 2015b; Ministère de l'Agriculture 2015/2016), which, in turn, incentivize farmers to change management, affecting all categories of soil management described in the following subsections.

In summary, ***consumer demand*** in combination with new ***technologies***, ***research***, and the change in ***farmers' attributes*** are the strongest drivers towards improved recognition of soil multifunctionality in soil management that have the potential to counteract the intensification pressure driven by increasing global biomass demands. ***Policies*** are not irrelevant, but they do not seem to show strong trends towards or against sustainable soil management. The role of tenure issues is not addressed in the literature for the case of Germany but may be worth investigating further given the fact that the share of rented land was already 60% in Germany in 2013 (Statistisches Bundesamt 2014a).

## 4.2 Spatial patterns

Spatial patterns of cropping systems determine the spatial extent and distribution of fields and crops as well as the quality of field transition zones, e.g., between different crops, fields, or land use types, including forests and grassland. Field transition zones affect erosion; agricultural biodiversity, likely including soil biodiversity; and biological pest control, allowing reduced pesticide application (Van Oost et al. 2000; Heißenhuber et al. 2014; FAO 2016b; Médiène et al. 2011; Haenke et al. 2014).

### 4.2.1 Field sizes, field patterns, and transition zones

The trend towards larger machinery for economic reasons (***factor costs***, especially labor costs) has led to increased field sizes (Björklund et al. 1999; Baessler and Klotz 2006) (Table 4). This situation has destroyed field margins and landscape elements such as hedgerows or small transition zones between crops. Although a trend reversal cannot be identified yet, certainly not for labor costs (European Commission 2015b), field transition zones may increase again due to increased knowledge and awareness about their positive impacts on soil functions (***soil degradation threats***, ***research***) (Table 4). Due to the adverse short-term cost-benefit relation for farmers, this alone will hardly suffice to motivate farmers to introduce field margins. However, in the coming decades, small, autonomous machines, for which the technology is currently being developed, may become implemented, among others, because the cost of machine work would be decoupled from labor costs (***ICT and robotics***, see Section 4.3). This would open opportunities for more small-scaled field patterns, especially if politicians create incentives to realize the possibilities. Currently, the green direct payments of CAP (***policies***) encourage landscape elements, although not very effectively (Pe’er et al. 2016; Zander et al. 2016b), and many, if not all, agri-environmental programs have been and are subsidizing landscape elements, flower strips, or other biotopes (Freese and Keelan 2016) (Table 4). Thus, drivers for smaller-scaled field patterns are evolving but to what degree the chances for this will be realized remains insecure.

### 4.2.2 Intercropping and agroforestry

Intercropping uses the positive effects of transition zones within the field by growing at least two crops simultaneously on one field. Similar to intercropping, agroforestry combines conventional agricultural crops or grassland with woody plants. Meta-studies show that intercropping has the potential for sustainable intensification by increasing both total yields

**Table 4** Drivers and trends regarding spatial patterns of soil management in Germany

| Drivers | Direction | Sources |
|---|---|---|
| 4.2.1 Field sizes and transition zones | | |
| *Factor costs* (labor) and *technology* development: increasing field sizes to accommodate larger machines | ↓ | Björklund et al. 1999; Baessler and Klotz 2006; European Commission 2015b; Jones et al. 2012 |
| *Policies*: CAP 1st and 2nd pillar measures already in place may be extended and become more effective in connection with new opportunities by *ICT and robotics* | ↑ | Freese and Keelan 2016, in connection with policies Section 4.1 |
| *Soil degradation threats:* biodiversity loss, erosion, and new research results may drive policies and adoption | ↑ | Björklund et al. 1999; Baessler and Klotz 2006; Van Oost et al. 2000; Heißenhuber et al. 2014; FAO 2016b; Médiène et al. 2011 |
| *ICT and robotics:* will facilitate smaller-scale management | ↑ | See Section 4.4.3 |
| 4.2.2 Intercropping and agroforestry | | |
| *Factors costs:* high investment costs and long return periods (mainly agroforestry) likely to keep on impeding adoption | ↓ | Nerlich et al. 2013; Musshoff 2012 |
| *Policies:* small steps towards rewarding these systems have been made and may be taken further | ↑ | Bundesministerium für Ernährung und Landwirtschaft 2015b in connection with policies Section 4.1 |
| *Climate change:* opportunities in relation to mitigation and adaptation may influence policy; *policies* for mitigation in general already exist | ↑ | Yu et al. 2015; Smith et al. 2013; Nerlich et al. 2013; Torralba et al. 2016; Lorenz and Lal 2014; Altieri et al. 2015; Lin 2011; Richard and El-Lakany 2015; Upson et al. 2016; Cardinael et al. 2017 in connection with climate change Section 4.1 |
| *Research* brings new insights, including positive impacts on soil functions (against *soil degradation threats*); research on agroforestry strongly increased | ↑ | Fagerholm et al. 2016; Pelzer et al. 2014; Yu et al. 2015; Nerlich et al. 2013; Torralba et al. 2016; Smith et al. 2013; Richard and El-Lakany 2015 |
| *Biomass technology:* developments to use more lignocellulosic feedstocks for energy and industry likely to bring opportunities for agroforestry | ↑ | See Section 4.3.1 |
| *ICT and robotics:* will facilitate smaller-scale management | ↑ | See Section 4.4.3 |

“↑” indicates management beneficial for soil functions. “↓” indicates management threatening soil functions. “?” indicates that there are no conclusions on the direction of the impact. Data in italics—drivers identified to affect soil management and soil functional changes in terms of land equivalent ratios and other ecosystem services, among others in temperate regions, including Europe (Pelzer et al. 2014; Yu et al. 2015). This relates to the increasing ***consumer demand*** for food and ***land availability*** constraints (Table 4). More research is needed to further substantiate this finding, especially for cereal/cereal combinations (Yu et al. 2015). In the case of agroforestry, a similar potential has been detected in review studies and a meta-analysis for Europe (Torralba et al. 2016; Nerlich et al. 2013) and for temperate regions in general (Smith et al. 2013).

***Research*** itself is a driver in this field, increasingly uncovering the potential impacts of intercropping and agroforestry in temperate zones, including Germany (Fagerholm et al. 2016 for agroforestry) (Table 4). Adoption of these practices will depend on their impact on farm income. This will more easily become positive for intercropping than for agroforestry because the latter is connected to higher investment costs (***factor costs***) and longer return rates (Table 4).

Because of the potential for sustainable intensification and ecosystem services, these systems may get promoted in the future by ***policies*** (Table 4). Since 2015, the CAP has recognized agroforestry fields as agricultural land eligible for basic payment from the first pillar, and it allows the financial promotion of agroforestry via the second pillar, recognizing it as an ecological focus area, which is currently not the case in Germany (Bundesministerium für Ernährung und Landwirtschaft 2015b). This shows an actual trend towards these systems, not just in the research arena. ***Climate change*** may also contribute to the adoption of both systems (Table 4). Studies reported increased carbon sequestration by intercropping (Yu et al. 2015) and agroforestry (Lorenz and Lal 2014; Smith et al. 2013; Torralba et al. 2016; Nerlich et al. 2013; Upson et al. 2016; Cardinael et al. 2017). Diversification, including measures such as intercropping and agroforestry, is generally associated with making agricultural systems more resilient to biophysical drivers such as climate change (potential for ***climate change*** adaptation) (Altieri et al. 2015; Lin 2011).

One of the strongest drivers for adopting intercropping and agroforestry may be technological development in the use of biomass for energy and industry (***biomass technology***) towards lignocellulosic feedstocks (see Section 4.3.1).

Finally, ***ICT and robotics*** may contribute as enabling drivers to the adoption of intercropping and agroforestry (Table 4). These drivers will enable much more precise and small-scaled management with small agricultural robots (see Section 4.4.3).

In summary, it is still very uncertain whether intercropping and agroforestry will become widespread practices in the coming decades. Still, there is a significant trend towards these systems, propelled by several drivers, and upcoming drivers may reinforce this trend.

## 4.3 Crops and rotations

The choice of crops and crop rotations affect soil functions because crops differ, for example, in their root systems, their interacting biological soil processes, their potential to dissolve nutrients, the degree and duration to which they cover the soil, and the residues they leave after harvest. Thus, they affect, for example, soil organic matter, soil stability and erosion, and soil biota.

### 4.3.1 Integration of lignocellulosic crops

There are technological and political advancements triggering the increase in lignocellulosic feedstocks for second-generation bioenergy (***biomass technology***) (Allwright and Taylor 2016; Stolarski et al. 2015; Chum et al. 2015) (Table 5). Aside from integrating these feedstocks directly with traditional crops such as grains or grass in agroforestry, short-rotation coppices (SRCs) with trees and *Miscanthus* monocultures are discussed and already implemented to a small degree. In addition, the potential of paludiculture for protecting organic soils from drainage and degradation is being discussed (Wissenschaftlicher Beirat Agrarpolitik et al. 2016; Wichmann 2016).

These systems are also considered to have some benefits for soil functions (driver ***soil degradation threats***), including carbon sequestration (***climate change*** mitigation) (Voigt 2015 for *Miscanthus*, Musshoff 2012 for SRC, Wichmann 2016 for paludiculture) (Table 5). The stress tolerance of some second-generation feedstocks such as *Miscanthus* (Quinn et al. 2015) makes them also of interest for ***climate change*** adaptation (Table 5). Responding to the potential for societal benefits, SRC can be acknowledged as an ecological focus area in Germany since the greening of the CAP, if certain specifications are implemented (Bundesministerium für Ernährung und Landwirtschaft 2015b). Some German federal states subsidize the establishment of SRC with up to 45% of investment costs (Fachagentur Nachwachsende Rohstoffe e.V. 2016). Thus, ***policies*** currently seem to be a driver for SRC though investment costs (***factor costs***), and the long payback periods are still barriers (Musshoff 2012).

Thus, the widespread integration of woody crops into agricultural systems is more likely a long-term option rather than a present trend.

### 4.3.2 Crop varieties

Farmers are expected to adapt to climate change-induced developments such as longer vegetation periods in the long term (past 2040) (Olesen et al. 2011; Mitter et al. 2015) and changed weed systems (Peters and Gerowitt 2014) by using different plant varieties (***climate change*** adaptation) (Table 5). Developing plant varieties in terms of their pathogen tolerance and their defense mechanisms below ground is a research

**Table 5** Drivers and trends regarding crops and crop rotations in Germany

| Drivers | Direction | Sources |
|---|---|---|
| 4.3.1. Integrating lignocellulosic crops | | |
| *Factor costs:* without policy support and better frame conditions, factor costs, especially investment costs, hinder implementation | ↓ | Musshoff 2012; Wichmann 2016; Nerlich et al. 2013 |
| *Policies:* short-rotation coppices (SRCs) can be acknowledged as ecological focus areas according to CAP; SRCs subsidized in some German states; support for the bioeconomy; support for biogas production has been reduced; official policy advisors recommend support for lignocellulosic bioenergy and consideration of paludicultures for protection of organic soils | ↑ | Bundesministerium für Ernährung und Landwirtschaft 2015b; Fachagentur Nachwachsende Rohstoffe e.V. 2016; Vollprecht et al. 2015; Bundesministerium für Ernährung und Landwirtschaft 2014; Commission 2012; Fachagentur Nachwachsende Rohstoffe e.V. 2015; Bioenergie e.V. et al. 2016b; Wissenschaftlicher Beirat Agrarpolitik et al. 2016 |
| *Climate change* and *soil degradation threats:* potential for increasing SOC and other environmental benefits; climate mitigation and adaption potential already impacting policies, potentially further support with more evidence of positive impacts | ↑ | Quinn et al. 2015; Voigt 2015; Musshoff 2012; Berndes et al. 2015; Wichmann 2016 |
| *Biomass technology:* developments to use more lignocellulosic feedstocks for energy and industry, potential for growing such feedstocks | ↑ | Stolarski et al. 2015; Chum et al. 2015; Allwright and Taylor 2016; Quinn et al. 2015; Berndes et al. 2015; Long et al. 2015; Voigt 2015; Schorling et al. 2015; Statistisches Bundesamt 2016a; Witzel and Finger 2016; Brosse et al. 2012; Musshoff 2012; Keutmann et al. 2016; Fachagentur Nachwachsende Rohstoffe e.V. 2014 |
| 4.3.2 Crop varieties | | |
| *Climate change:* adaptation with different crop varieties | ↑ | Olesen et al. 2011; Mitter et al. 2015; Peters and Gerowitt 2014 |
| *Research:* developing varieties for better pathogen resistance | ↑ | Johnson et al. 2016; Rasmann et al., 2017 |
| *Research/technology:* new breeding methods might lead to organisms, such as varieties of agricultural annual crops, that may harm ecosystems, thus also the soil ecosystem | ↓ | Science for Environment Policy 2016 |
| 4.3.3 Crop rotations: diversity, cover crops, and legumes | | |
| *Policies:* already a little support (CAP, agri-environmental measures) for diversity, cover crops and legumes, debate on further "greening" of the CAP | ↑ | Freese and Keelan 2016; Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz 2012; Statistisches Bundesamt 2016b; Zander et al. 2016a; Reckling et al. 2016 in connection with policies under 1 |
| *Policies:* support for bioenergy has led to less diverse crop rotations and grassland loss, incentives reduced but still an uncertain process, especially considering potential changes in feedstocks | ? | Laggner et al. 2014; Bioenergie e.V. et al. 2016b; Fachagentur Nachwachsende Rohstoffe e.V. 2015; Vollprecht et al. 2015; Bundesministerium für Ernährung und Landwirtschaft 2014; Bioenergie e.V. et al. 2016a in connection with Section 4.3.1 |
| *Soil degradation threats, climate change,* and *research* showing increasingly positive effects on soil functions and climate change mitigation and adaptation potentially leading to changed behavior, inter alia via policies | ↑ | Bronick and Lal 2005; Johnson et al. 2016; McDaniel et al. 2014; Poeplau and Don 2015; Olesen et al. 2011; Techen 2015; Friedrichsen 2016 in connection with policies |
| *Climate change:* adaptation with less diverse crop rotations in some areas | ↓ | Nendel et al. 2014; Troost and Berger 2015; Gutzler et al. 2015; Peters and Gerowitt 2014 |
| *Consumer demand:* potentially increasing demand for lignocellulosic crops | | See Section 4.3.1 |
| *Consumer demand:* increasing demand for organic, local and diversified food | | Bund Ökologische Lebensmittelwirtschaft 2012, 2016; Hempel and Hamm 2016; Last et al. 2015; Schindler et al. 2014; Teagasc 2016 |

"↑" indicates management beneficial for soil functions. "↓" indicates management threatening soil functions. "?" indicates that there are no conclusions on the direction of the impact. Data in italics—drivers identified to affect soil management and soil functional changes

topic that may also become more practically relevant in the future once ***research*** has advanced (Johnson et al. 2016; Rasmann et al. 2017) (Table 5). New breeding technologies, such as CRISPR/cas9, can also lead to organisms, including varieties of annual agricultural crops, which can bring risks, such as harming ecosystems (Science for Environment Policy 2016) which could also have an impact on agricultural soils.

### 4.3.3 Crop rotations: diversity, cover crops, and legumes

For crop rotations, there are drivers in opposite directions: On the one hand, diversifying crop rotations and/or including non-harvested cover crops and legumes induce improved soil functions in terms of nutrient cycling, soil microbial biomass, and soil biota with relevance for plant health, soil carbon content (meta-studies by McDaniel et al. 2014; Poeplau and Don 2015; review by Johnson et al. 2016), and soil structure with relevance for soil erosion (Bronick and Lal 2005). As such, these measures are useful for counteracting ***soil degradation threats***, including soil biodiversity loss, and mitigating ***climate change*** (Table 5). These positive aspects for soil functions are the reason they are already subsidized by the CAP green direct payment (Bundesministerium für Ernährung und Landwirtschaft 2015b) and by agri-environmental measures in some German states (Freese and Keelan 2016). The effectiveness of these policy measures is contested, but the further development of agricultural policy may bring more relevant policy incentives (***policies***) (Table 5). In addition, the German government's "protein crops strategy," including influences on the CAP towards the support of grain legumes (Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz 2012), seems to be leading to higher shares of legumes on cropland, though currently affecting less than 1% of cropland (Statistisches Bundesamt 2016b; Reckling 2016; Zander et al. 2016a). The positive effects of enhanced crop rotations on soil functions can also be driven by adaptations to ***climate change*** because higher carbon contents of soils and better soil structure make agricultural systems more resilient to climate change (Olesen et al. 2011) (Table 5). These circumstances are met by farmers with a general awareness of the relevance of crop rotation for soil fertility (Friedrichsen 2016; Techen 2015).

On the other hand, the economics related to ***climate change*** with longer vegetation periods and higher temperatures, if not mitigated by policies, are expected to lead to less diverse/narrower crop rotations in some areas in Germany (Gutzler et al. 2015; Troost and Berger 2015; Peters and Gerowitt 2014) and double cropping, e.g., growing a summer barley after a winter barley, will become possible in some regions (Nendel et al. 2014).

A key driver of crop rotations is ***demand from consumers***, which determines which crops are economically feasible (Table 5). In that respect, the potentially increasing demand for lignocellulosic plants for second-generation bioenergy (***biomass technology***) seems to be the main driver (see Section 4.3.1). From 2000 until recently, the promotion of bioenergy with the Renewable Energy Sources Act (EEG) (***policies***) was a driver of less sustainable crop rotations, and presumably also of turning grassland into cropland (Laggner et al. 2014), due to the incentives for high shares of maize in the rotations. Meanwhile, the EU has put a measure into place to stop grassland loss in the context of cross-compliance, and the reforms of the EEG in 2012 and 2014 have reduced incentives to produce maize as feedstock for biogas—and biogas at all—while the 2016 reform (EEG 2017) will likely lead to a stabilization of the policy incentives (Bioenergie e.V. et al. 2016a, b). Additionally, if the demand of consumers is significantly changing towards more organic, more local, and more diverse food (see Section 4.1), then this might already have a small but increasing impact on crop diversity and crop rotations.

Most of these drivers are rather long term. A policy change towards diversified crop rotations may be the fastest but not the strongest driver.

## 4.4 Mechanical pressures on soil

Mechanical pressures on soil can damage soil structure, lead to compaction and erosion, and disturb soil biota, all severely damaging soil functions, including the production function (Schjønning et al. 2015).

### 4.4.1 Tillage

Reduced tillage is a widespread practice in Germany with 38% of cropland having been under reduced tillage and 1% under zero tillage in 2009/2010 (Statistisches Bundesamt 2010). More innovative and not yet widespread forms are strip-tillage and controlled traffic farming (CTF) as well as innovative methods of subsoil management, some of which go beyond tillage (see Section 4.4.2).

High costs of labor and fossil fuels (***factor costs***) are drivers of reduced tillage (Flessa et al. 2012; Techen 2015) (Table 6). Factor costs are likely to increase (European Commission 2015b). In addition, awareness of ***soil degradation threats*** (***farmers' attributes***) is an incentive for farmers to reduce tillage (Techen 2015) (Table 6). Both are likely established factors rather than trends, but they may be drivers for the diffusion of new (strip-till, CTF) or future technologies (***ICT and robotics***) (Table 6). In addition, ***climate change*** adaptation is expected to drive reduced tillage because it is an important water-saving practice in some European countries, including the eastern half of Germany (Olesen et al. 2011). Reduced tillage is also discussed in the context of ***climate change*** mitigation because of its beneficial effect on carbon sequestration in the upper soil layer (e.g., Zandersen et al. 2016), although this effect is strongly contested (Powlson et al. 2014; Baker et al. 2007; Blanco-Canqui and Lal 2008; VandenBygaart 2016). Reduced tillage had been subsidized in some German states in the past (Grajewski and Schmidt 2015). Currently, there are still agri-environmental measures (***policies***) for reduced tillage in 4 out of the 16 German states, all but one specifically for strip-tillage and zero tillage (Freese and Keelan 2016).

One trend may potentially reduce the share of reduced tillage. There are political debates on pesticide use reflecting consumers' concerns (***consumers' demand***)

**Table 6** Drivers and trends regarding mechanical pressures on soil management in Germany

| Drivers | Direction | Sources |
|---|---|---|
| 4.4.1 Tillage | | |
| *Factor costs:* less fuel and waiting time for reduced tillage | ↑ | Flessa et al. 2012; Techen 2015; Statistisches Bundesamt 2010; European Commission 2015b |
| *Farmers' attributes* and *soil degradation threats:* awareness is a factor for the adoption of soil conserving tillage that may still increase | ↑ | Techen 2015 in connection with soil threats and farm(er)s attributes under 4.1 |
| *Policies:* subsidizing with agri-environmental measures now occurs primarily for strip-till and zero-till, aiming at long-term adoption | ↑ | Grajewski and Schmidt 2015; Freese and Keelan 2016 |
| *Policies:* restrictive policies on pesticides are being debated that would lead to less reduced tillage | ↓ | Kehlenbeck et al. 2015; Agra-Europe 2016d; European Commission 2016a; Redaktion DLG-Mitteilungen 2016; Conseil constitutionnel 2016 |
| *Climate change:* reduced tillage debated as beneficial for adaptation and for mitigation | ↑ | Olesen et al. 2011; Zandersen et al. 2016; Baker et al. 2007; Blanco-Canqui and Lal 2008; Powlson et al. 2014; VandenBygaart 2016 |
| *Technology:* site-specific tillage is being developed | ↑ | Auernhammer and Demmel 2015; Jørgensen 2014; Stoorvogel et al. 2015 |
| 4.4.2 Subsoil management | | |
| *Factor costs:* subsoiling is costly, factor costs are likely to increase, and this may constrain implementation | ↓ | European Commission 2015b; Chamen et al. 2015 |
| *Policies:* C sequestration in arable soils is a topic in international political debate but seems less relevant in Germany, except for organic soils | ↑ | Ministère de l'Agriculture 2015/2016; Wissenschaftlicher Beirat Agrarpolitik et al. 2016; Deutsche Bundesregierung 2016; Paris Agreement 2015 |
| *Soil degradation threats:* subsoil compaction is a problem; currently, awareness is weak, but it may increase with more *research* and improved monitoring with technological progress through *ICT* | ↑ | Jones et al. 2012; Prager and Curfs 2016 in connection with research here and ICT in Sections 4.4.3 and 4.5.1 |
| *Climate change:* mitigation and adaptation, including water conservation, ongoing research and upcoming insights | ↑ | Alcantara et al. 2016; Kell 2012; Lorenz and Lal 2005; Kassam et al. 2013; Sang et al. 2016 |
| *Resource scarcity* and *research:* higher nutrient efficiency through subsoil management | ↑ | Zhang et al. 2016; Ekelöf et al. 2015 |
| 4.4.3 Weight and contact stresses | | |
| *Factor costs* (labor) with *technology* development: ongoing trend towards heavier machines | ↓ | Chamen et al. 2015; Jones et al. 2012; Schjønning et al. 2015 |
| *Factor costs* (labor): factor for adoption of technology saving labor | ↑ | Auernhammer and Demmel 2015 |
| *Soil degradation threats:* compaction is a production constraining factor in Germany and a driver of *research* | ↑ | Marahrens et al. 2015 |
| *Research and technology:* development of technical solutions, e.g., full automatic tire pressure regulation or optimization of field traffic | ↑ | Brunotte and Lorenz 2015; Auernhammer and Demmel 2015; Lorenz et al. 2016; Bochtis et al. 2012; Edwards et al. 2016; Weltzien and Gebbers 2016; Han et al. 2015; Agra-Europe 2016a |
| *Technology:* controlled traffic farming (CTF) potential for Europe is still being assessed | ↑ | Antille et al. 2015; Chamen et al. 2015; Demmel et al. 2012; Preuße 2016 |
| *ICT and robotics:* small, light autonomous agricultural robots for different purposes in crop and grassland production are being developed and will allow labor costs to be reduced | ↑ | Auernhammer and Demmel 2015; Blackmore 2015; Conesa-Muñoz et al. 2015; Chevalier et al. 2015; Liebisch et al. 2016; AGCO GmbH and Fendt-Marketing 2015; Meuli 2016; Rowbot Systems 2016; Naïo Technologies 2016b; ecoRobotix Ltd. 2016; Bechar and Vigneault 2016 in connection with Section 4.5.1 |

"↑" indicates management beneficial for soil functions. "↓" indicates management threatening soil functions. "?" indicates that there are no conclusions on the direction of the impact. Data in italics—drivers identified to affect soil management and soil functional changes

(Table 6). The near ban of glyphosate and the ban of neonicotinoids in neighboring France (***policies***) are examples. A ban of glyphosate would not just mean less pesticide input, it would very likely lead to more frequent tillage and an increased share of tillage with the plow, at least until new pesticides will substitute glyphosate (Kehlenbeck et al. 2015, Section 4.5.2).

Additionally, site-specific tillage (***technology, ICT***) (Fig. 4), which determines the tillage depth according to factors such as soil type and moisture, has the potential to make

**Fig. 4** In front of the tractor, a sensor detects soil texture via the conductivity. Sandy soil with low conductivity is being tilled at a deeper working depth than a clayey soil with high conductivity. Data acquisition and implementation are done in real time. (photo credits: Hans-Heinrich Voßhenrich)

tillage more beneficial for the soils, especially once better on-the-go soil moisture sensors are available (Auernhammer and Demmel 2015: 314 f., similarly, Jørgensen 2014; Stoorvogel et al. 2015: 53).

The bottom line is that the existing drivers in favor of the adoption of improved and new tillage technologies may be counteracted in the short to medium term by pesticide restrictive policies and investment costs of new technologies.

### 4.4.2 Subsoil management

The management of subsoil has different facets. One is subsoiling, that is deep plowing to break the plow layer and traffic-induced compaction, and in some cases, adding organic material to the subsoil. This approach can be used in combination with subsequent no-till to improve water storage and availability for plants (Kassam et al. 2013). The other aspect of subsoiling is to breed and cultivate suitable plants, manipulating soil fauna and microorganisms, also in combination with reduced tillage (Lorenz and Lal 2005; Kell 2012).

Subsoil compaction from heavy machinery and plowing is a ***soil degradation threat*** in Europe, including Germany (Jones et al. 2012) (Table 6). At the same time, it is very difficult to recognize and is thus not sufficiently addressed by farmers (Jones et al. 2012). ***Research*** is a key driver here because potential new measures of and additional arguments for subsoil management seem to be primarily discussed within the scientific community. Therein, subsoil management is discussed in terms of sequestering carbon (***climate change*** mitigation) (Kell 2012; Alcantara et al. 2016; Lorenz and Lal 2005), water conserving tillage (***climate change*** adaptation) (Sang et al. 2016), and phosphorous efficiency (***resource scarcity***) (Ekelöf et al. 2015; Zhang et al. 2016). Thus, research is now providing more arguments for subsoil management in relation to current societal challenges, thereby potentially creating a meaningful impact. Especially in terms of C sequestration, the subsoil is understood to be a long-term sink because of the physical protection of the overlying topsoil. Differences in the subsoil texture compared to the topsoil may as well affect the carbon sequestration potential (Alcantara et al. 2016). The research fits well with current ***policies*** of the UNFCCC's Paris Agreement (Paris Agreement 2015) and the "4 per 1000" initiative (Ministère de l'Agriculture 2015/2016), of which Germany is part. However, Germany's "National Climate Action Plan for 2050" (Deutsche Bundesregierung 2016) does not entail carbon sequestration in mineral arable soils, nor is it identified as a relevant measure in the recent national experts' report on climate change mitigation in the agricultural and neighboring sectors (Wissenschaftlicher Beirat Agrarpolitik et al. 2016). In addition, the costs (***factor costs***) of deep tillage (Chamen et al. 2015) are a natural opponent of that aspect of this trend, and factor costs are likely to increase (European Commission 2015b).

Overall, with research in an early stage still being the main driver of modern subsoil management that supports soil functions, while policy drivers are undetermined, and factor costs are hampering, the development of subsoil management is uncertain.

### 4.4.3 Weight and contact stresses

High labor costs (***factor costs***) and the development of agricultural ***technology*** have been driving an increase in the weight of machinery for decades in Europe (Schjønning et al. 2015) (Table 6). Some measures to address compaction have offset part of the increasing pressure but not sufficient to reverse the trend of increasing compaction (Jones et al. 2012). Similarly, high labor costs seem to hamper the adoption of such measures because they require more working and/or waiting time, for example, to adjust tire pressure between the field and the road and avoiding driving in the fields when the soil is too wet (Chamen et al. 2003). A trend reversal cannot be identified currently, certainly not for labor costs (European Commission 2015b) and not for the weight of machines (Jones et al. 2012).

Still, in the medium to long term, soil compaction can decrease yields (Chamen et al. 2015; Schjønning et al. 2015). Based on spot tests, Marahrens et al. (2015) estimated that compaction has already led to soil functions being impaired on 20% of the German cropland. Approximately 50% of German soils are estimated to be vulnerable to compaction (Marahrens et al. 2015). Thus, compaction as a ***soil degradation threat*** is a driver of research and maybe a driver of developing and adopting less compacting technologies.

One option is "controlled traffic farming" (CTF) (***technology***), which has been investigated and adopted mostly in other parts of the world, especially in Australia (Antille et al. 2015; Demmel et al. 2012) (Table 6). For European conditions, no unequivocal knowledge of the impacts of the approach is available (Chamen et al. 2015). Practitioners seem to be skeptical about the usefulness of CTF in Germany (Preuße 2016). ***Research*** on CTF is occurring in some European countries, including Germany, and may drive its adoption in the long term (Demmel et al. 2012) (Table 6).

A further option for reducing mechanical stress is decision support systems (DSSs) that optimize field traffic more individually (***research* and *technology***) (Table 6). The first step is calculating fieldwork patterns and guiding the tractors so that minimal overlap occurs. This practice also saves labor costs (***factor costs***) due to time savings (Auernhammer and Demmel 2015), which may drive its adoption. Automatic tire pressure regulation is currently being developed (Brunotte and Lorenz 2015). Further, DSSs are being developed that can integrate more soil data from different sources and optimize routes, loads, and tire pressure in terms of soil compaction (Bochtis et al. 2012; Lorenz et al. 2016). Such technologies still have challenges in the areas of on-the-go sensing of soil characteristics, sensor/data fusion, and generating practical decision support (Bechar and Vigneault 2016; Han et al. 2015; Weltzien and Gebbers 2016). In addition, improved DSSs are being developed to determine the days of trafficability and workability for the specific field operations (Edwards et al. 2016; Lorenz et al. 2016).

In the long term, ***ICT and robotics*** development may lead to much lighter machines. For some purposes, small, lightweight robots are being developed, and few first variants are already on the market or shortly before commercialization (ecoRobotix Ltd. 2016 (Fig. 1); Naïo Technologies 2016a, b; Rowbot Systems 2016). Their further adoption still faces technological and organizational challenges as well as legal issues (Auernhammer and Demmel 2015). Nonetheless, broad implementation of small robot fleets is envisioned (Auernhammer and Demmel 2015; Blackmore 2015) and prepared by researchers (e.g., Chevalier et al. 2015; Conesa-Muñoz et al. 2015; Liebisch et al. 2016) and agricultural technologies companies (AGCO GmbH and Fendt-Marketing 2015). The fact that those agricultural robots are unmanned vehicles that are envisioned to operate as fleets will disconnect the weight of the machines from labor costs. Their large-scale adoption could relieve much pressure from the soils, while there is no scientific evidence yet that shows where there is an optimal balance between stress from machine size/weight and stress from the frequency of running over the field.

Thus, ***research*** and technological development (***technology***, ***ICT and robotics***), together with ***factor costs*** of the farms, drive measures that are likely to bring some relief to the weight and contact stresses of soils in the short and long term if the evolving opportunities are realized.

## 4.5 Inputs into the soil

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

### 4.5.1 Precise application

The efficiency of resource use, such as fertilizers and pesticides, can be improved with new technologies. ***Factor costs*** (Schindler et al. 2014), increasing with ***resource scarcity***, and ***consumer demand*** concerning environmental issues (see Section 4.1) are drivers for this (Table 7). Examples are the use of small robots for precise herbicide application on or mechanical destruction of weeds identified with sensors (Meuli 2016) (Fig. 1). Needed technologies, including robots, drones, (on-the-go) sensors for soil characteristics, data fusion algorithms, translation into decision-support systems, infrastructure with GNSS (global navigation satellite system), and mobile networks, are under development (***ICT and robotics***). Thus, a more precise application can be expected in the long term.

### 4.5.2 Pesticides

Aside from the precision of pesticide application (Section 4.5.1), the authorization of pesticides may become more strict. As outlined in Section 4.4.1, ***consumer demand*** is establishing a trend towards more pesticide restrictive ***policies*** (Table 7). The outcome of this ongoing debate is still uncertain. The primary effects of a ban of glyphosate would likely be decreased chemical disturbances of soil biota and decreased emissions of pesticides and their metabolites to other environmental media. This is because for arable land, there are currently almost no appropriate chemical alternatives (Kehlenbeck et al. 2015). Instead, more physical disturbances of soils because of increased tillage with the plow would most likely occur in the short-term (Section 4.4.1). In the medium or long term, a ban could result in increased use of other pesticides, which may be more or less harmful to the environment than glyphosate (Kehlenbeck et al. 2015). New pesticides may become available with yet unknown properties regarding persistence, mobility, and interference with soil biodiversity.

***Climate change*** is likely to alter and partially increase weed pressures (Peters and Gerowitt 2014) and other pests in Germany and Central Europe (Richerzhagen et al. 2011;

**Table 7** Drivers and trends regarding the use of soil inputs in Germany

| Drivers | Direction | Sources |
|---|---|---|
| 4.5.1 Precise application | | |
| *Factor costs*, including costs because of *resource scarcity* | ↑ | Schindler et al. 2014 |
| *Consumer demand* concerning the environment | ↑ | See Section 4.1 |
| *ICT and robotics:* progress concerning, among others, precise application and needed infrastructure | ↑ | Meuli 2016; Teagasc 2016; Weltzien and Gebbers 2016; mb 2016; Han et al. 2015; Ribeiro et al. 2015; Liebisch et al. 2016; Chevalier et al. 2015; Schmidhalter et al. 2008; Fountas et al. 2015b; Garbers 2015; Commission 2016a, b; European Commission 2016b; 5G Infrastructure Public Private Partnership 2015 in connection with ICT & robotics in 4.4.3 |
| *Policies:* supporting the development of needed infrastructure and technologies | ↑ | Commission 2016b; European Commission 2016b; Agra-Europe 2016a |
| 4.5.2 Pesticides | | |
| *Consumer demand* potentially leading to policies restrictive of specific pesticides, potentially leading to less pesticide application | ↑ | Agra-Europe 2016d; European Commission 2016a; Redaktion DLG-Mitteilungen 2016; Conseil constitutionnel 2016 |
| *Consumer demand* potentially leading to *policies* restrictive of specific pesticides, potentially leading to more frequent tillage and higher shares of tillage with the plow | ↓ | Kehlenbeck et al. 2015 in connection with directly above |
| *Climate change* adaptation: changes in weeds and pests will require changes in pesticide usage | ? | Peters and Gerowitt 2014; Richerzhagen et al. 2011; Juroszek and von Tiedemann 2013; Lamichhane et al. 2016; Peters et al. 2014 |
| *Research* on measures to improve soil biodiversity affecting resilience against pathogens and reducing the need for pesticides; precise application (see 5.1) reduces amounts used | ↑ | Johnson et al. 2016 and ICT and robotics in 5.1 for precise application |
| *ICT and robotics:* more precision brings opportunities for less input | ↑ | See Section 4.5.1 |
| 4.5.3 Organic inputs | | |
| *Farmers' attributes* and *soil threats:* awareness of soil threats, including organic matter decline, is already a factor for adoption but may still have a positive influence on the adoption of new options | ↑ | Techen 2015 in connection with soil threats and farm(er)s attributes under 4.1 and 4.3.3 |
| *Policies:* together with *research* insights, societal goals and policies on biodiversity may drive policies supporting organic matter build-up | ↑ | COP to the CBD 2010a, b; Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2007 |
| Increasing *research,* including monitoring improvements in Europe, to show the positive effects of different organic inputs on soil biodiversity *(soil threats)* and *climate change* mitigation and adaptation | ↑ | Stone et al. 2016; Alcantara et al. 2016; FAO 2016b; Diacono and Montemurro 2010; Larkin 2015; Thies et al. 2015; Smith et al. 2013; Berndes et al. 2015; Griffiths et al. 2016 in connection with 4.3.3 |
| *Biomass technology:* potential development towards including lignocellulosic feedstocks in agricultural systems leading to more organic residues | ↑ | See Section 4.3.1 |
| *Biomass technology:* plant residues discussed as feedstock for bioenergy and industry in the future | ↓ | Long et al. 2015; Caicedo et al. 2016; Berndes et al. 2015; Weiser et al. 2014; Hennig et al. 2016; Thrän et al. 2016 |
| 4.5.4 New fertilizers from recycled nutrients | | |
| *Resource scarcity* and *factor costs* (also other nutrients): incentives for technological development and adoption | ? | Marahrens et al. 2015; Trott 2010 |
| *Research/technology:* development towards improved recycling methods, but impacts on soil still unclear, contaminants are still a problem | ↓ | Desmidt et al. 2015; Montag et al. 2015 |
| *Research/technology:* potentially better distributions of P sources in the country, reducing oversupply in some and undersupply in other regions. | ↑ | Trott 2010 for current over- and undersupply of some agricultural soils in Germany; Hjorth et al. 2016 |
| *Policies:* debating and supporting the development of nutrient recycling and the commercialization of products | ? | Wissenschaftlicher Beirat für Düngungsfragen beim BMELV 2011; Kommission Bodenschutz beim Umweltbundesamt 2015; European Commission 2015a, 2016c; Ekardt et al. 2015; Fertilizers Europe 2016a, b |
| *Research:* is ongoing in academia and industry | ? | Fertilizers Europe 2016b; Desmidt et al. 2015; Montag et al. 2015 |

Juroszek and von Tiedemann 2013; Lamichhane et al. 2016) (Table 7). This factor must affect plant protection strategies,

**Table 7** (continued)

| Drivers | Direction | Sources |
|---|---|---|
| 4.5.5 Inoculation of soil and seeds with, and management of, mutualists of crops and natural enemies of pests | | |
| *Factor costs:* costs of measures expected to be hurdles for implementation, at least in the near future for inoculation and medium to long term for more sophisticated measures like improved crop rotations | ↓ | Johnson et al. 2016 |
| *Research* bringing new insights into how to generate positive effects on plant production through microbial inoculation | ↑ | Johnson et al. 2016; Saia et al. 2015a; Saia et al. 2015b; Zhang et al. 2014; Verbruggen et al. 2012; El-Sirafy et al. 2006; Rasmann et al. 2017; Kergunteuil et al. 2016; Larkin 2015 |
| *Research, soil threats:* generally positive effects on soil habitat function if pesticides can be avoided because of inoculation with natural enemies | ↑ | Kergunteuil et al. 2016 |
| *Policies:* If not studied and regulated enough, inoculants could reach the market that may affect non-targeted organisms negatively | ↓ | Kergunteuil et al. 2016 |
| *Research* bringing new insights on promoting local mutualists of crops and natural enemies of pests | ↑ | Johnson et al. 2016; Rasmann et al. 2017; Larkin 2015 |
| *Technology:* improved methods to assess soil biota and derive management options expected | ↑ | Teagasc 2016 |
| 4.5.6 Irrigation | | |
| *More* irrigation is expected due to *climate change* in the long term | ? | Münch et al. 2014; Nendel et al. 2014; Statistisches Bundesamt 2014c; Gutzler et al. 2015; Riediger et al. 2016 |

"↑" indicates management beneficial for soil functions. "↓" indicates management threatening soil functions. "?" indicates that there are no conclusions on the direction of the impact. Data in italics—drivers identified to affect soil management and soil functional changes

including pesticide application. The trends are still uncertain (Juroszek and von Tiedemann 2013; Peters et al. 2014).

Enhancing soil biodiversity can strengthen soil resilience towards pathogens. In their review, Johnson et al. (2016) find significant long-term potential of applying, for example, biocontrol agents such as entomopathogenic nematodes to the soil, affecting soil biota while considerable research still seems to be required to effectively reduce pesticide application, making ***research*** a driver (Table 7).

With highly insecure policy development and climate change impacts and new technologies still being in the research stage, no clear trend can be identified for utilization of pesticides (aside from more precise application).

### 4.5.3 Organic input

Farmers have long been aware of the important role of organic matter in soil fertility. For example, approximately half of 694 Hessian farmers who grow cover crops named the humus balance as one of their motivations (Techen et al. 2015: 75). Maintaining the soil organic matter level was relevant for cross-compliance from 2005 to 2014 as an alternative to some crop rotation standards (DirektZahlVerpflV § 3).

There is no sign that organic matter decline (***soil degradation threats***) is a singular driver for changes in soil management even though in combination with other drivers, it does play a role in changing soil management (Table 7). Orgiazzi et al. (2016) found that organic matter decline in agricultural soils was one of the two highest threats to soil biodiversity (***soil degradation threats***). Soil biodiversity loss may induce a trend towards an increased organic input into the soil, as ***research*** brings new insights along with better monitoring in the EU (Griffiths et al. 2016; Stone et al. 2016) and societal goals and ***policies*** are in place (COP to the CBD 2010a, b; Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2007). Reviews showed that the effects of long-term organic amendments such as compost had very positive effects on soil microbial biomass, enzymatic activity (Diacono and Montemurro 2010), and biodiversity (Larkin 2015). Another review showed that amendments such as biochar can enhance soil biodiversity, but there is still much need for further research (Thies et al. 2015). A related measure, also increasing organic input and microbial biomass, is growing cover crops as green manure (see Section 4.3.3). Agroforestry and other systems, including perennials, discussed in Sections 4.2 and 4.3.1, also increase organic matter input and improve soil invertebrate communities and soil biodiversity as a whole (Smith et al. 2013; Berndes et al. 2015).

In addition, by increasing SOC, organic inputs are strongly linked to ***climate change*** mitigation and adaptation, e.g., by putting organic matter into the subsoil (Alcantara et al. 2016).

Although biomass production for energy and industry (***biomass technology***) offers potential opportunities for increased organic input from cultivating lignocellulosic perennials in the future (see Section 4.3.1), it has opposite effects as well. The use of plant residues for energy production and industry has been identified as a method to avoid directly losing acreage for food production (Long et al. 2015). This class of feedstock may be strengthened to some degree by breeding dual-purpose crops (Caicedo et al. 2016). Withholding plant residues can put considerable pressure on soils by preventing the maintenance of soil organic matter with all its functions and ecosystem services (Berndes et al. 2015). Considering this circumstance, Weiser et al. (2014) still estimate that between 53 and 89% of the technical potential of straw in Germany could be sustainably used for bioenergy. In the short run, it is likely that only a small share of this potential will be used because of technical constraints such as low energy density and long transport distances due to dispersed cultivation (Hennig et al. 2016). In the long run, technical circumstances may improve, for example, through further development and by removing institutional barriers of market uptake of the torrefaction technology (Hennig et al. 2016; Thrän et al. 2016). Thus, in the future, the usage of plant residues may become a pressure on agricultural soils depending on technological and political developments.

Even though there are drivers pointing to opposing directions, it does seem like the relevance of organic input is gaining broader awareness, and this may lead to actions counteracting organic matter decline in places where it is relevant.

### 4.5.4 New fertilizers from recycled nutrients

The recycling of substances such as sludge and slurry in fertilizer production, such as phosphate, is a topic of ***research*** and ***technology*** development and discussion in academia, industry, and politics. This process may have different influences on soils, including its contamination with substances like heavy metals, depending on the original material and its treatment (Desmidt et al. 2015; Montag et al. 2015).

The drivers for such recycling are ***factor costs*** and especially ***resource scarcity***. In Germany, some agricultural soils are oversupplied with phosphorous (P) to the extent that it is a threat to other ecosystems (Marahrens et al. 2015: 19) (Table 7). Other agricultural soils are rather poorly supplied. An analysis of the data from most German federal states showed that 28% of cropland and 51% of grassland are undersupplied with P (Trott 2010). Processes like improved slurry separation may contribute to better distributing P and N (nitrogen) between regions by making the nutrients more worthy of transport (Hjorth et al. 2010). The necessity for efficient P use is a topic at the interface of research and the political agenda in Germany (Kommission Bodenschutz beim Umweltbundesamt 2015; Wissenschaftlicher Beirat für Düngungsfragen beim BMELV 2011), and the European Commission is paving the way for adjusted fertilizer regulations (European Commission 2016c) in the context of the Action Plan for the Circular Economy (European Commission 2015a) and the Raw Materials Strategy (Ekardt et al. 2015) (***policies***). In addition, part of the fertilizer industry is working towards recycling nutrients while emphasizing that the framework conditions are not yet fully developed (Fertilizers Europe 2016a, b) (***research***).

Thus, there is a clear trend towards recycling nutrients for fertilizers while it is still unsure when and what kind of change exactly will occur.

### 4.5.5 Inoculation of soil and seeds with, and management of, mutualists of crops and natural enemies of pests

Biotic inoculation of soils and seeds is seen by some authors (Johnson et al. 2016, Kergunteuil et al. 2016) as an evolving, promising method for plant performance and protection.

Important below ground mutualists for crops that can improve crop productivity and promote indirect plant defenses, among others when added by inoculation, are bacteria and fungi (Rasmann et al. 2017). Positive effects on plant growth by soil inoculation with bacteria or fungi were found, for example, in wheat in Sicily (Saia et al. 2015a), China (Zhang et al. 2014), and Egypt (El-Sirafy et al. 2006), whereas findings of negative effects (Verbruggen et al. 2012) underline that the interdependencies are not well understood yet (Saia et al. 2015b) (Table 7).

Natural enemies of belowground pests are manifold. They include viruses, bacteria, fungi, nematodes, and arthropods (Kergunteuil et al. 2016). High potential for inoculation with such organisms is seen for several types of natural enemies, such as entomopathogenic nematodes (EPNs) (Johnson et al. 2016 and Kergunteuil et al. 2016) and mixes, such as EPNs with *Bacillus thuringiensis* (Kergunteuil et al. 2016). For some organisms, effects on non-targeted organisms are not sufficiently studied yet. But in general, negative effects are much less expected than from chemical pesticides (Kergunteuil et al. 2016). Wide application of inoculation with natural enemies is still hindered by technical and economic obstacles, including ***factor costs*** (Johnson et al. 2016 and Kergunteuil et al. 2016), so that currently, ***research***, including industrial research, seems to be the decisive driver towards inoculation of soil with natural enemies.

While inoculation is an innovative method that may evolve and gain adoption, there are more conventional ways to promote local mutualists of crops and natural enemies of pests, such as crop rotations, cover crops and intercropping (Johnson et al. 2016, Larkin 2015), organic amendments, especially compost (Larkin 2015), and breeding plants to attract mutualists (Rasmann et al. 2017).

Inoculation of soil with, and management of, soil biota is the pressure most explicitly associated with soil biodiversity loss as a driver (***soil degradation threats***) (Section 4.5.3). Inoculation may still be a rather expensive measure for compensating for soil biodiversity loss, carrying also the risk of damaging non-targeted organisms if measures are not studied and regulated enough (***policies***). In the long run, it is likely to become cheaper. Farmers may perceive this practice as an easy option that does not require as substantial changes to the production systems as other measures, even though the effectiveness of the inoculation may strongly depend on supporting measures (Johnson et al. 2016). Teagasc (2016) expects that by 2035, it will be routine in agriculture to collect genetic data from soil biota (***technology***) and use the information together with available data from other sources for management decisions, including isolating and utilizing endophytes to enhance the soil biome. There are still significant challenges to overcome to reach this goal, such as to develop sensors and algorithms (Section 4.5.1).

Pesticides will likely be the cheapest version for fighting plant diseases in the near future. But upcoming research and technology together with increased awareness of the relevance of soil biota may pave the way towards the wide-spread adoption of inoculation with crop mutualists and natural enemies of pests in the future and potentially also towards agricultural management which promotes the local soil biotic communities.

### 4.5.6 Irrigation

Irrigation is not widespread in Germany. In 2012, only 4% of German agricultural areas had the infrastructure for irrigation and only 2% were actually irrigated (Statistisches Bundesamt 2014c).

Several studies found economic potential for irrigation in some areas in Germany at present and increasingly in the future, towards 2070, due to ***climate change***, with high variabilities among regions and soil types (Nendel et al. 2014; Münch et al. 2014; Riediger et al. 2016) (Table 7). Conflicts with other water uses can occur in drier years in northeastern Germany (Steidl et al. 2015), restricted water extraction rights may hamper irrigation, and investments in irrigation infrastructure are less likely on rented land (Münch et al. 2014). At the same time, even in one of the German states with the lowest annual rainfall, Brandenburg, Gutzler et al. (2015) found that water availability would likely be a problem in only 2 out of 14 districts.

Thus, there is a clear trend towards an increased introduction of irrigation in Germany as a reaction to climate change in the long run.

## 5 Conclusions

The analysis of the drivers and trends of soil management in Germany present challenges as well as opportunities for maintaining or improving soil functions presently and in the coming decades. Challenges stem largely from agricultural intensification, which will likely have less impact in Germany than worldwide. More challenges stem mainly from factor costs and risks associated with new practices. Factor costs are projected to remain stable or even increase in relation to the product prices and are an obstacle to the adoption of some beneficial practices, more so in short than in the long term. Risks usually come along with emerging practices because their impacts are not sufficiently understood. There are, however, also great opportunities for agricultural soils posed especially by the technological development towards including smaller and lighter machines and more precise management, by research that is increasingly uncovering positive effects of some soil improving production methods on soil quality and yield development, and by a societal will to support sustainable production methods or subsidiary aspects such as the SOC content of agricultural soils.

Some solutions for the challenges will be developed and opportunities seized by farmers and the farming industry; some changes will be initiated by policy measures. However, the realization of opportunities is not self-evident. Soil and agricultural research can play a vital role in developing sustainable and effective methods of soil management in this framework of drivers, for example, to incorporate lignocellulosic crops in agricultural productions systems to seize the opportunities stemming from improved biomass technologies and policy strategies. It is also crucial for researchers to cooperate in analyzing the unfolding management changes, their alternatives, and their impacts on soil processes so that they can provide evidence for sound suggestions to farmers, authorities, politicians, and society. Basic and applied research must interact in a systemic approach to better understand the soil reaction to changing management and to understand the value of soil functions for societal value systems, particularly in terms of ecosystem services, resource efficiency, and ethical and equity considerations. Only then appropriate governance systems can be developed that integrate bioeconomy with sustainable development targets.

The analysis showed that for many upcoming management practices, little scientific evidence about their effect on soil processes and functions exists, especially on the habitat for biodiversity function. Researchers will need to further develop knowledge about the interaction between soil management and soil functions. To capture the long-term impacts of potentially drastic changes under semi-controlled conditions, long-term field experiments are very valuable. For example, new fertilizers added over a long period potentially accumulate substances, which do not seem relevant in the short-term observation. The analysis particularly requires a systemic view on the soil processes and an interdisciplinary approach involving soil scientists, agricultural scientists, natural scientists, and socio-economic scientists, and the latter to also conduct sustainability assessments of soil management trends that bring a wider understanding of intended and unintended impacts of soil management on sustainability targets. Cooperation with practitioners may improve research results to be well-founded and accepted by farmers.

This review showed that there are a number of changes that might occur in agricultural soil management depending on how different drivers develop. On this basis, future soil management scenarios can be built in the frame of different driver configurations to further determine crucial research topics and needs for action.

The conclusions are not just true for Germany but can be transferred generally to other countries. Many drivers presented here are global, such as food demand and aspects of technological development, or European, such as many of the policies. In addition, for each country, there are distinctions such as the climate, infrastructure, and educational level of the farmers. Our driver-pressures framework for soil management (Fig. 2) can be useful for researchers analyzing soil management and trends in other countries. With additional case studies, a more robust, generic framework may be developed.

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## References

5G Infrastructure Public Private Partnership (2015) 5G Vision. The 5G Infrastructure Public Private Partnership: the next generation of communication networks and services. https://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf. Accessed 12 Sept 2016

AGCO GmbH, Fendt-Marketing (2015) Project MARS: research in the field of agricultural robotics. Precision farming—thinking ahead. AGCO GmbH, Fendt-Marketing. http://www.fendt.com/int/11649.asp. Accessed 7 Nov 2016

Agra-Europe (2016a) Bundeslandwirtschaftsministerium fördert big-data-projekte. Agra-Europe 08.08.2016: L 28

Agra-Europe (2016b) EU-Agrarminister sagen der bürokratie den kampf an. Agra-Europe 06.06.2016: EU 1

Agra-Europe (2016c) Immer mehr landwirte mit agrarstudium. Agra-Europe 04.06.2016: L 26

Agra-Europe (2016d) Kommission beschließt verlängerung der glyphosat-zulassung. Agra-Europe 04.07.2016: EU 7–8

Agra-Europe (2016e) Über uns - Agra-Europe. Agra-Europe Presse- und Informationsdienst GmbH. http://www.agra-europe.de/ueber-uns/agra-europe.html. Accessed 15 Sept 2016

Agra-Europe (2017) Grünes Licht für das Düngepaket. Agra-Europe 03.04.2017: L 40

Albrecht K, Ettling S (2014) Bioeconomy strategies across the globe. Rural 21(03/2014):10–13

Alcantara V, Don A, Well R, Nieder R (2016) Deep ploughing increases agricultural soil organic matter stocks. Glob Chang Biol 22(8): 2939–2956. https://doi.org/10.1111/gcb.13289

Alexander P, Rounsevell MDA, Dislich C, Dodson JR, Engström K, Moran D (2015) Drivers for global agricultural land use change: the nexus of diet, population, yield and bioenergy. Glob Environ Chang 35:138–147. https://doi.org/10.1016/j.gloenvcha.2015.08.011

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. Working paper No. 12–03. FAO. http://www.fao.org/docrep/016/ap106e/ap106e.pdf. Accessed 4 Apr 2016

Allwright MR, Taylor G (2016) Molecular breeding for improved second generation bioenergy crops. Trends Plant Sci 21(1):43–54. https://doi.org/10.1016/j.tplants.2015.10.002

Alston JM, Pardey PG, Ruttan VW (2008) Research lags revisited: concepts and evidence from U.S. Agriculture. Staff Paper P08-14; InSTePP Paper 08-02, International Science and Technology Practice and Policy Center (InSTePP). Department of Applied Economics. http://ageconsearch.umn.edu/handle/50091. Accessed 9 Aug 2016

Altieri MA, Nicholls CI, Henao A, Lana MA (2015) Agroecology and the design of climate change-resilient farming systems. Agron Sustain Dev 35(3):869–890. https://doi.org/10.1007/s13593-015-0285-2

Anon (2016) People4Soil. https://www.people4soil.eu/en/about. Accessed 19 Dec 2016

Antille DL, Chamen WCT, Tullberg JN, Lal R (2015) The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in arable land: a critical review. Trans ASABE 58(3):707–731. 10.13031/trans.58.11049

Auernhammer H, Demmel M (2015) State of the art and future requirements. In: Zhang Q (ed) Precision agriculture technology for crop farming. CRC Press, Boca Raton, pp 299–342. https://doi.org/10.1201/b19336-11

Baessler C, Klotz S (2006) Effects of changes in agricultural land-use on landscape structure and arable weed vegetation over the last 50 years. Agric Ecosyst Environ 115(1–4):43–50. https://doi.org/10.1016/j.agee.2005.12.007

Bai ZG, Dent DL, Olsson L, Schaepman ME (2008) Proxy global assessment of land degradation. Soil Use Manag 24(3):223–234. https://doi.org/10.1111/j.1475-2743.2008.00169.x

Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration—what do we really know? Agric Ecosyst Environ 118(1–4):1–5. https://doi.org/10.1016/j.agee.2006.05.014

Baumgart-Getz A, Prokopy LS, Floress K (2012) Why farmers adopt best management practice in the United States: a meta-analysis of the adoption literature. J Environ Manag 96(1):17–25. https://doi.org/10.1016/j.jenvman.2011.10.006

Bechar A, Vigneault C (2016) Agricultural robots for field operations: concepts and components. Biosyst Eng 149:94–111. https://doi.org/10.1016/j.biosystemseng.2016.06.014

Berndes G, Youngs H, Ballesterc MVR, Cantarellad H, Cowiee AL, Jewittf G, Martinellig LA, Neary D (2015) Soils and water. In: Mendes Souza C, Victoria RL, Joly CA, Verdade LM (eds) Bioenergy and sustainablitiy: bridging the gaps. SCOPE 72. Scientific Committee on Problems of the Environment (SCOPE), Paris, pp 618–659

Bioenergie e.V, Deutscher Bauern verband e.V, Fachverband Biogas e.V, Fachverband Holzenergie (2016a) Gemeinsame pressemitteilung: verbesserungen im EEG für anlagenbetreiber erreicht. http://www.biogas.org/edcom/webfvb.nsf/id/DE-Gemeinsame-PM-16-12-2016?open&ccm=050. Accessed 16 Dec 2016

Bioenergie e.V, Deutscher Bauern verband e.V, Fachverband Biogas e.V, Fachverband Holzenergie (2016b) Gemeinsames positionspapier: kurzbewertung des EEG 2017 vom 08.07.2016. BBE. http://www.biogas.org/edcom/webfvb.nsf/id/DE_Gemeinsame-PM-08-07-2016/$file/BBE_DBV_FvB_FVH_Kurzbewertung_EEG_2017%20[08.07.2016].pdf. Accessed 20 Sept 2016

Björklund J, Limburg KE, Rydberg T (1999) Impact of production intensity on the ability of the agricultural landscape to generate ecosystem services: an example from Sweden. Ecol Econ 29(2):269–291. https://doi.org/10.1016/S0921-8009(99)00014-2

Blackmore S (2015) Toward robotic agriculture. Resour Mag 22(2):27

Blanco-Canqui H, Lal R (2008) No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci Soc Am J 72(3):693–701. https://doi.org/10.2136/sssaj2007.0233

Bochtis DD, Sørensen CG, Green O (2012) A DSS for planning of soil-sensitive field operations. Decis Support Syst 53(1):66–75. https://doi.org/10.1016/j.dss.2011.12.005

Bronick CJ, Lal R (2005) Soil structure and management: a review. Geoderma 124(1–2):3–22. https://doi.org/10.1016/j.geoderma.2004.03.005

Brosse N, Dufour A, Meng X, Sun Q, Ragauskas A (2012) *Miscanthus*: a fast-growing crop for biofuels and chemicals production. Biofuel Bioprod Biorefin 6(5):580–598. https://doi.org/10.1002/bbb.1353

Brunotte J, Lorenz M (2015) Anpassung der Lasteinträge landwirtschaftlicher Maschinen an die Verdichtungsempfindlichkeit von Böden – Wunschtraum oder bereits Realität? Paper presented at the Tagungsband "Jahr des Bodens" Schwere Maschinen, enge Fruchtfolgen, Gärreste – eine Gefahr für die Bodenfruchtbarkeit? Fachtagung 13. Kulturlandschaftstag, 18–19 Juni 2015

Bund Ökologische Lebensmittelwirtschaft (2012) Zahlen Daten Fakten. Die Bio-Branche 2012. Bund Ökologische Lebensmittelwirtschaft, Berlin

Bund Ökologische Lebensmittelwirtschaft (2016) Zahlen Daten Fakten. Die Bio-Branche 2016. Bund Ökologische Lebensmittelwirtschaft, Berlin

Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (2012) Eiweißpflanzenstrategie des BMELV Stand: 27.11.2012. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz, Berlin

Bundesministerium für Ernährung und Landwirtschaft (2014) Nationale Politikstrategie Bioökonomie. Nachwachsende ressourcen und biotechnologische verfahren als basis für ernährung, industrie und energie. Bundesministerium für Ernährung und Landwirtschaft, Berlin

Bundesministerium für Ernährung und Landwirtschaft (2015a) Agrarpolitischer Bericht der Bundesregierung 2015. Bundesministerium für Ernährung und Landwirtschaft, Berlin

Bundesministerium für Ernährung und Landwirtschaft (2015b) Umsetzung der EU-Agrarreform in Deutschland. Ausgabe 2015. Bundesministerium für Ernährung und Landwirtschaft. Bundesministerium für Ernährung und Landwirtschaft, Berlin

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (2007) Nationale Strategie zur biologischen Vielfalt. Kabinettsbeschluss vom 7. November 2007. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, Berlin

Buth M, Kahlenborn W, Savelsberg J, Becker N, Bubeck P, Kabisch S, Kind C, Tempel A, Tucci F, Greiving S, Fleischhauer M, Lindner C, Lückenkötter J, Schonlau M, Schmitt H, Hurth F, Othmer F, Augustin R, Becker D, Abel M, Bornemann T, Steiner H, Zebisch M, Schneiderbauer S, Kofler C (2015) Vulnerabilität Deutschlands gegenüber dem Klimawandel. Climate Change 24/2015. Umweltbundesamt, Dessau-Roßlau

Caicedo M, Barros J, Ordás B (2016) Redefining agricultural residues as bioenergy feedstocks. Materials 9(8):635. https://doi.org/10.3390/ma9080635

Cardinael R, Chevallier T, Cambou A, Béral C, Barthès BG, Dupraz C, Durand C, Kouakoua E, Chenu C (2017) Increased soil organic carbon stocks under agroforestry: a survey of six different sites in France. Agric Ecosyst Environ 236:243–255. https://doi.org/10.1016/j.agee.2016.12.011

Chalak A, Abou-Daher C, Chaaban J, Abiad MG (2016) The global economic and regulatory determinants of household food waste generation: a cross-country analysis. Waste Manag 48:418–422. https://doi.org/10.1016/j.wasman.2015.11.040

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(1–2):161–174. https://doi.org/10.1016/S0167-1987(03)00108-9

Chamen WCT, Moxey AP, Towers W, Balana B, Hallett PD (2015) Mitigating arable soil compaction: a review and analysis of available cost and benefit data. Soil Tillage Res 146(Part A):10–25. https://doi.org/10.1016/j.still.2014.09.011

Chevalier A, Copot C, De Keyser R, Hernandez A, Ionescu C (2015) A multi agent system for precision agriculture. In: Busoniu L, Tamás L (eds) Handling uncertainty and networked structure in robot control. Springer International Publishing, Cham, pp 361–386. https://doi.org/10.1007/978-3-319-26327-4_15

Chum HL, Nigro FEB, McCormicka R, Beckhama GT, Seabrac JEA, Saddlerd J, Taoa L, Warnera E, Overenda RP (2015) Conversion technologies for biofuels and their use. In: Mendes Souza C, Victoria RL, Joly CA, Verdade LM (eds) Bioenergy and sustainablitiy: bridging the gaps. SCOPE 72. Scientific Committee on Problems of the Environment (SCOPE), Paris, pp 374–467

Clermont-Dauphin C, Blanchart E, Loranger-Merciris G, Meynard J-M (2014) Cropping systems to improve soil biodiversity and ecosystem services: the outlook and lines of research. In: Ozier-Lafontaine H, Lesueur-Jannoyer M (eds) Sustainable agriculture reviews 14: agroecology and global change. Springer International Publishing, Cham, pp 117–158. https://doi.org/10.1007/978-3-319-06016-3_5

Colinet L, Joly P-B, Gaunand A, Matt M, Larédo P, Lemarié S (2014) ASIRPA – Analyse des Impacts de la Recherche Publique Agronomique. Rapport final. INRA, Paris

Commission E (2012) Innovating for sustainable growth. A bioeconomy for Europe Publications Office of the European Union, Luxembourg. https://doi.org/10.2777/6462

Commission E (2016a) Galileo. European Union. http://ec.europa.eu/growth/sectors/space/galileo_en. Accessed 12 Sept 2016

Commission E (2016b) Galileo satellite launches. European Union. http://ec.europa.eu/growth/sectors/space/galileo/launches_en. Accessed 12 Sept 2016

Conesa-Muñoz J, Gonzalez-de-Soto M, Gonzalez-de-Santos P, Ribeiro A (2015) Distributed multi-level supervision to effectively monitor the operations of a fleet of autonomous vehicles in agricultural tasks. Sensors 15(3):5402–5428. https://doi.org/10.3390/s150305402

Conseil constitutionnel (2016) Décision n° 2016–737 DC du 4 août 2016

COP to the CBD (2010a) Decision adopted by the conference of the parties to the convention on biological diversity at its tenth meeting X/2. The strategic plan for biodiversity 2011–2020 and the aichi biodiversity targets. UNEP/CBD/COP/DEC/X/2

COP to the CBD (2010b) Decision adopted by the conference of the parties to the convention on biological diversity at its tenth meeting X/5. Implementation of the convention and the strategic plan UNEP/CBD/COP/DEC/X/5

Demmel M, Brandhuber R, Kirchmeier H, Müller M, Marx M (2012) Controlled traffic farming—technical and organizational realization. Landtechnik 67(6):435–440

Desmidt E, Ghyselbrecht K, Zhang Y, Pinoy L, Bruggen BVD, Verstraete W, Rabaey K, Meesschaert B (2015) Global phosphorus scarcity and full-scale P-recovery techniques: a review. Crit Rev Environ

Sci Technol 45(4):336–384. https://doi.org/10.1080/10643389.2013.866531

Deutsche Bundesregierung (2002) Perspektiven für Deutschland. Unsere Strategie für eine nachhaltige Entwicklung. Die Bundesregierung, Berlin

Deutsche Bundesregierung (2016) Klimaschutzplan 2050. Beschlossen am 14.11.2016. Die Bundesregierung, Berlin

Deutsche Bundesregierung (2017) Deutsche nachhaltigkeitsstrategie. Neuauflage 2016. (Kabinettbeschluss vom 11. Januar 2017). Die Bundesregierung, Berlin

Diacono M, Montemurro F (2010) Long-term effects of organic amendments on soil fertility. A review. Agron Sustain Dev 30(2):401–422. https://doi.org/10.1080/10643389.2013.866531

DirektZahlVerpflV Verordnung über die Grundsätze der Erhaltung landwirtschaftlicher Flächen in einem guten landwirtschaftlichen und ökologischen Zustand (Direktzahlungen-Verpflichtungenverordnung - DirektZahlVerpflV). V. v. 04.11.2004 BGBl. I S. 2778; aufgehoben durch § 11 V. v. 17.12.2014 BAnz AT 23.12.2014 V1

DLG-Mitteilungen R (2016) Information. Deutsche landwirtschafts-gesellschaft. http://www.dlg-mitteilungen.de/ueber-uns/information/. Accessed 15 Sept 2016

Duru M, Therond O, Martin G, Martin-Clouaire R, Magne M-A, Justes E, Journet E-P, Aubertot J-N, Savary S, Bergez J-E, Sarthou JP (2015) How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron Sustain Dev 35(4):1259–1281. https://doi.org/10.1007/s13593-015-0306-1

ecoRobotix Ltd. (2016) Project presentation. ecoRobotix Ltd. http://www.ecorobotix.com/category/project/. Accessed 15 Jun 2016

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

Ekardt F, Garske B, Stubenrauch J, Wieding J (2015) Legal instruments for phosphorus supply security. J Euro Environ Plan Law 12(3-4): 343–361. https://doi.org/10.1163/18760104-01204007

Ekelöf J, Guamán V, Jensen ES, Persson P (2015) Inter-row subsoiling and irrigation increase starch potato yield, phosphorus use efficiency and quality parameters. Potato Res 58(1):15–27. https://doi.org/10.1007/s11540-014-9261-5

El-Sirafy ZM, Woodard HJ, El-Norjar EM (2006) Contribution of biofertilizers and fertilizer nitrogen to nutrient uptake and yield of Egyptian winter wheat. J Plant Nutr 29(4):587–599. https://doi.org/10.1080/01904160600564287

Emberger-Klein A, Zapilko M, Menrad K (2016) Consumers' preference heterogeneity for GM and organic food products in Germany. Agribusiness 32(2):203–221. https://doi.org/10.1002/agr.21439

Erjavec K, Erjavec E (2015) 'Greening the CAP'—just a fashionable justification? A discourse analysis of the 2014–2020 CAP reform documents. Food Policy 51:53–62. https://doi.org/10.1016/j.foodpol.2014.12.006

EU SCAR, Standing Committee on Agricultural Research (2016) Agricultural knowledge and innovation systems towards the future—a foresight paper. https://doi.org/10.2777/324117

European Bioplastics (2015) Bioplastics market data. http://www.european-bioplastics.org/market/. Accessed 20 Apr 2016

European Commission (2002) Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions—towards a thematic strategy for soil protection. COM/2002/0179 final

European Commission (2011) Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions roadmap to a resource efficient Europe. COM/2011/0571 final

European Commission (2013) Decision No 1386/2013/EU of the european parliament and of the council of 20 November 2013 on a general union environment action programme to 2020 'Living well, within the limits of our planet' text with EEA relevance

European Commission (2014) Communication from the commission to the european parliament and the council european energy security strategy. COM/2014/0330 final

European Commission (2015a) Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions. Closing the loop—An EU action plan for the Circular Economy. COM(2015) 614 final

European Commission (2015b) EU agricultural outlook. Prospects for EU agricultural markets and income 2015–2025

European Commission (2016a) Factsheet. FAQs glyphosate. European Commission, Brussels

European Commission (2016b) Horizon 2020. Work Programme 2016–2017. 5.i. Information and communication technologies. European Commission Decision C(2016)4614 of 25 July 2016

European Commission (2016c) Proposal for a regulation of the European Parliament and of the Council laying down rules on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009. COM(2016) 157 final

Fachagentur Nachwachsende Rohstoffe e.V (2014) Anbauentwicklung nachwachsender Rohstoffe auf landwirtschaftlichen Flächen in Deutschland, 2000 bis 2014. Fachagentur Nachwachsende Rohstoffe e.V. http://bioenergie.fnr.de/bioenergie/energiepflanzen/. Accessed 12 Aug 2016

Fachagentur Nachwachsende Rohstoffe e.V (2015) Entwicklung der Maisanbaufläche in Deutschland. Fachagentur Nachwachsende Rohstoffe e.V. https://mediathek.fnr.de/grafiken/daten-und-fakten/bioenergie/biogas/entwicklung-der-maisanbauflache-in-deutschland.html. Accessed 28 Oct 2016

Fachagentur Nachwachsende Rohstoffe e.V (2016) Förderung von Kurzumtriebsplantagen in den Bundesländern. Fachagentur Nachwachsende Rohstoffe e.V. http://bioenergie.fnr.de/rahmenbedingungen/foerderung/kup-foerderung/. Accessed 25 Oct 2016

Fagerholm N, Torralba M, Burgess PJ, Plieninger T (2016) A systematic map of ecosystem services assessments around European agroforestry. Ecol Indic 62:47–65. https://doi.org/10.1016/j.ecolind.2015.11.016

FAO (1982) World soil charter. Food and Agriculture Organization, Rome

FAO (2013a) FAO statistical yearbook 2013. World food and agriculture. Food and Agriculture Organization, Rome

FAO (2013b) Food wastage footprint. Impacts on natural resources. Summary report. Food and Agriculture Organization, Rome

FAO (2015a) FAO statistical pocketbook 2015. World food and agriculture. Food and Agriculture Organization, Rome

FAO (2015b) Revised world soil charter. Food and Agriculture Organization, Rome

FAO (2016a) SAVE FOOD: Global initiative on food loss and waste reduction. FAO. http://www.fao.org/save-food/en/. Accessed 20 Apr 2016

FAO (2016b) Voluntary guidelines for sustainable soil management. Adopted by the fourth global soil partnership plenary assembly. 06/2016

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 Soil, Rome

Fertilizers Europe (2016a) Conference summary: opportunities in the EU fertilizer regulation: what to look out for? Fertilizers Europe. http://fertilizerseurope.com/index.php?id=531&no_cache=1&cid=1294&did=35101&sechash=992d2970. Accessed 18 Nov 2016

Fertilizers Europe (2016b) Position paper: the EU's new regulation on fertilizing products must maintain the quality of Europe's fertilizers.

Fertilizers Europe. http://fertilizerseurope.com/index.php?id=531&no_cache=1&cid=1294&did=35167&sechash=1c236199. Accessed 18 Nov 2016

Flessa H, Müller D, Plassmann K, Osterburg B, Techen A-K, Nitsch H, Nieberg H, Sanders J, Meyer zu Hartlage O, Beckmann E, Anspach V (2012) Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, vol SH 361. Landbauforschung. Johann-Heinrich von Thünen-Institut, Braunschweig

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockstrom J, Sheehan J, Siebert S, Tilman D, DPM Z (2011) Solutions for a cultivated planet. Nature 478(7369):337–342. https://doi.org/10.1038/nature10452

Foresight (2011) The future of food and farming. Final project report. The Government Office for Science, London

Fountas S, Carli G, Sørensen CG, Tsiropoulos Z, Cavalaris C, Vatsanidou A, Liakos B, Canavari M, Wiebensohn J, Tisserye B (2015a) Farm management information systems: current situation and future perspectives. Comput Electron Agric 115:40–50. https://doi.org/10.1016/j.compag.2015.05.011

Fountas S, Sorensen CG, Tsiropoulos Z, Cavalaris C, Liakos V, Gemtos T (2015b) Farm machinery management information system. Comput Electron Agric 110:131–138. https://doi.org/10.1016/j.compag.2014.11.011

Fraser EDG (2004) Land tenure and agricultural management: soil conservation on rented and owned fields in southwest British Columbia. Agric Hum Values 21(1):73–79. https://doi.org/10.1023/B:AHUM.0000014020.96820.a1

Freese J, Keelan S (2016) ELER in Deutschland. Übersicht über die in den Programmen der Länder angebotenen Maßnahmen. Bundesanstalt für Landwirtschaft und Ernährung. DVS - Deutsche Vernetzungsstelle Ländliche Räume, Bonn

Friedrichsen P (2016) Was kostet Fruchtfolge? DLG-Mitteilungen, vol 2016. Deutsche Landwirtschafts-Gesellschaft, Frankfurt/Main

Garbers H (2015) Digitale Zukunft braucht Lösungen, nicht Schlagworte. Landtechnik 70(6):218–220. 10.15150/lt.2015.2677

Gardi C, Panagos P, Van Liedekerke M, Bosco C, De Brogniez D (2015) Land take and food security: assessment of land take on the agricultural production in Europe. J Environ Plan Manag 58(5):898–912. https://doi.org/10.1080/09640568.2014.899490

Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M, Hoffmann I, Smith P, Thornton PK, Toulmin C, Vermeulen SJ, Godfray HCJ (2013) Sustainable intensification in agriculture: premises and policies. Science 341(6141):33–34. https://doi.org/10.1126/science.1234485

General Assembly (2015) Transforming our world: the 2030 Agenda for Sustainable Development, A/RES/70/1

Gindele N, Kapsa S, Doluschitza R (2015) Strukturelle veränderungen in der landwirtschaft – reaktion der landwirtschaftlichen betriebsleiter sowie ableitbare konsequenzen für den landwirt als unternehmer. J Socio-Econ Agric 8:11–20

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

Godfray HCJ, Robinson S (2015) Contrasting approaches to projecting long-run global food security. Oxf Rev Econ Policy 31(1):26–44. https://doi.org/10.1093/oxrep/grv006

Gömann H, Bender A, Bolte A, Walter Dirksmeyer, Englert H, Feil J-H, Frühauf C, Hauschild M, Krengel S, Lilienthal H, Löpmeier F-J, Müller J, Mußhoff O, Natkhin M, Offermann F, Seidel P, Schmidt M, Seintsch B, Steidl J, Strohm K, Zimmer Y (2015) Agrarrelevante extremwetterlagen und möglichkeiten von risikomanagementsystemen. Studie im auftrag des bundesministerium für ernährung und landwirtschaft (BMEL); Abschlussbericht: Stand 3.6.2015. Thünen-Report 30. Johann Heinrich von Thünen-Institut, Braunschweig. https://doi.org/10.3220/REP1434012425000

Grajewski R, Schmidt T (2015) Agrarumweltmaßnahmen in Deutschland - Förderung in den ländlichen Entwicklungsprogrammen im Jahr 2013. Thünen Working Paper 44. doi:https://doi.org/10.3220/WP1440484615000

Gray I, Phillips E, Dunn T (2000) Aspects of rural culture and the use of conservation farming. In: Shulman A, Price R (eds) Case studies in increasing the adoption of sustainable resource management practices. Land and Water Resources Research and Development Corporation, Canberra, pp 32–45

Griffiths BS, Römbke J, Schmelz RM, Scheffczyk A, Faber JH, Bloem J, Pérès G, Cluzeau D, Chabbi A, Suhadolc M, Sousa JP, Martins da Silva P, Carvalho F, Mendes S, Morais P, Francisco R, Pereira C, Bonkowski M, Geisen S, Bardgett RD, de Vries FT, Bolger T, Dirilgen T, Schmidt O, Winding A, Hendriksen NB, Johansen A, Philippot L, Plassart P, Bru D, Thomson B, Griffiths RI, Bailey MJ, Keith A, Rutgers M, Mulder C, Hannula SE, Creamer R, Stone D (2016) Selecting cost effective and policy-relevant biological indicators for European monitoring of soil biodiversity and ecosystem function. Ecol Indic 69:213–223. https://doi.org/10.1016/j.ecolind.2016.04.023

Gustavsson J, Cederberg C, Sonesson U, van Otterdijk R, Meybeck A (2011) Global food losses and food waste. Extent, causes and prevention. Food and Agriculture Organization, Rome

Gutzler C, Helming K, Balla D, Dannowski R, Deumlich D, Glemnitz M, Knierim A, Mirschel W, Nendel C, Paul C, Sieber S, Stachow U, Starick A, Wieland R, Wurbs A, Zander P (2015) Agricultural land use changes—a scenario-based sustainability impact assessment for Brandenburg, Germany. Ecol Indic 48:505–517. https://doi.org/10.1016/j.ecolind.2014.09.004

Haddaway NR, Hedlund K, Jackson LE, Kätterer T, Lugato E, Thomsen IK, Jørgensen HB, Söderström B (2015) What are the effects of agricultural management on soil organic carbon in boreo-temperate systems? Environ Evid 4(1):23. https://doi.org/10.1186/s13750-015-0049-0

Haenke S, Kovács-Hostyánszki A, Fründ J, Batáry P, Jauker B, Tscharntke T, Holzschuh A (2014) Landscape configuration of crops and hedgerows drives local syrphid fly abundance. J Appl Ecol 51(2):505–513. https://doi.org/10.1111/1365-2664.12221

Han S, Steward BL, Tang L (2015) Intelligent agricultural machinery and field robots. In: Zhang Q (ed) Precision agriculture technology for crop farming. CRC Press, Boca Raton, pp 133–176. https://doi.org/10.1201/b19336-6

Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO, Townshend JRG (2013) High-resolution global maps of 21st-century forest cover change. Science 342(6160):850–853. https://doi.org/10.1126/science.1244693

Heißenhuber A, Haber W, Krämer C (2014) 30 Jahre SRU-Sondergutachten "Umweltprobleme der Landwirtschaft" - eine Bilanz. TEXTE 28/2015. Umweltbundesamt, Dessau-Roßlau

Hempel C, Hamm U (2016) Local and/or organic: a study on consumer preferences for organic food and food from different origins. Int J Consum Stud 40(6):732–741. https://doi.org/10.1111/ijcs.12288

Hennig C, Brosowski A, Majer S (2016) Sustainable feedstock potential—a limitation for the bio-based economy? J Clean Prod 123:200–202. https://doi.org/10.1016/j.jclepro.2015.06.130

Herre R (2013) Land concentration, land grabbing and options for change in Germany. Land concentration, land grabbing and people's struggles in Europe. Transnational Institute (TNI) for European Coordination Via Campesina and Hands off the Land network. https://www.tni.org/files/download/04._germany.pdf. Accessed 14 Oct 2016

Hjorth M, Christensen KV, Christensen ML, Sommer SG (2010) Solid–liquid separation of animal slurry in theory and practice. A review. Agron Sustain Dev 30(1):153–180. https://doi.org/10.1051/agro/2009010

Hogan P (2016) Speaking Points of Commissioner Phil Hogan at the Informal EU Agriculture Council in the Netherlands on 31 May 2016. European Commission. http://ec.europa.eu/agriculture/commissioner-speeches/pdf/hogan-2016-05-31-plenary-session.pdf. Accessed 7 Jun 2016

IEA (2015) Energy climate and change. World energy outlook special report. OECD/International Energy Agency, Paris

Institute for Bioplastics and Biocomposites, nova-Institut für Ökologie und Innovation, European Bioplastics (2015) Global bioploymer production capacity, last updated on 28.10.2015. http://ifbb.wp.hs-hannover.de/downloads/content/Statistics/Market%20statistics/Production%20capacities/Global%20biopolymer%20production%20capacity.png. Accessed 20 Apr 2016

IPCC (2014) Summary for policymakers. In: Field VRB CB, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Climate change 2014: impacts, adaptation, and vulnerability. Part a: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 1–32

Isermeyer F (2014) Künftige Anforderungen an die Landwirtschaft − Schlussfolgerungen für die Agrarpolitik. Thünen Working Paper 30. https://doi.org/10.3220/WP_30_2014

Johnson SN, Benefer CM, Frew A, Griffiths BS, Hartley SE, Karley AJ, Rasmann S, Schumann M, Sonnemann I, Robert CAM (2016) New frontiers in belowground ecology for plant protection from root-feeding insects. Appl Soil Ecol 108:96–107. https://doi.org/10.1016/j.apsoil.2016.07.017

Jones A, Panagos P, Barcelo S, Bouraoui F, Bosco C, Dewitte O, Gardi C, Erhard M, Hervás J, Hiederer R, Jeffery S, Lükewille A, Marmo L, Montanarella L, Olazábal C, Petersen J-E, Penizek V, Strassburger T, Tóth G, Eeckhaut MVD, Liedekerke MV, Verheijen F, Viestova E, Yigini Y (2012) The State of Soil in Europe. A contribution of the JRC to the European Environment Agency’s Environment State and Outlook Report—SOER 2010. https://doi.org/10.2788/77361

Jørgensen MH (2014) Adaptive tillage systems. Agron Res 12(1):95–100

Juroszek P, von Tiedemann A (2013) Climate change and potential future risks through wheat diseases: a review. Eur J Plant Pathol 136(1):21–33. https://doi.org/10.1007/s10658-012-0144-9

Kassam A, Basch G, Friedrich T, Shaxson F, Goddard T, Amado TJC, Crabtree B, Hongwen L, Mello I, Pisante M, Mkomwa S (2013) Sustainable soil management is more than what and how crops are grown. In: Lal R, Stewart BA (eds) Principles of sustainable soil management in agroecosystems. CRC Press, Taylor & Francis Group, Boca Raton, pp 337–400

Kastner T, Rivas MJI, Koch W, Nonhebel S (2012) Global changes in diets and the consequences for land requirements for food. Proc Natl Acad Sci USA 109(18):6868–6872. https://doi.org/10.1073/pnas.1117054109

Kay S, Peuch J, Franco J (2015) Extent of farm land grabbing in the EU. European Parliament, Brussels

Kehlenbeck H, Saltzmann J, Schwarz J, Zwerger P, Nordmeyer H, Roßberg D, Karpinski I, Strassemeyer J, Golla B, Freier B (2015) Folgenabschätzung für die Landwirtschaft zum teilweisen oder vollständigen Verzicht auf die Anwendung von glyphosathaltigen Herbiziden in Deutschland. Julius-Kühn-Archiv 451. Julius Kühn-Institut, Quedlinburg. https://doi.org/10.5073/jka.2015.451.000

Kell DB (2012) Large-scale sequestration of atmospheric carbon via plant roots in natural and agricultural ecosystems: why and how. Philos Trans R Soc Lond Ser B Biol Sci 367(1595):1589–1597. https://doi.org/10.1098/rstb.2011.0244

Kergunteuil A, Bakhtiari M, Formenti L, Xiao Z, Defossez E, Rasmann S (2016) Biological control beneath the feet: a review of crop protection against insect root herbivores. Insects 7(4):70. https://doi.org/10.3390/insects7040070

Keutmann S, Uckert G, Grundmann P (2016) Insights into a black box! Comparison of organizational modes and their monetary implications for the producers of short rotation coppice (SRC) in Brandenburg/Germany. Land Use Policy 57:313–326. https://doi.org/10.1016/j.landusepol.2016.05.024

Kolokotsa D (2017) Smart cooling systems for the urban environment. Using renewable technologies to face the urban climate change. Sol Energy 154:101–111. https://doi.org/10.1016/j.solener.2016.12.004

Kommission Bodenschutz beim Umweltbundesamt (2015) Position: Schonung von Phosphor-Ressourcen aus Sicht einer nachhaltigen Bodennutzung und des Bodenschutzes. https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/schonung_von_phosphor-ressourcen_aus_sicht_einer_nachhaltigen_bodennutzung_und_des_bodenschutzes.pdf

Laggner B, Orthen N, Osterburg B, Röder N (2014) Ist die zunehmende Biogasproduktion die alleinige Ursache für den Grünlandschwund in Deutschland? – eine Analyse von georeferenzierten Daten zur Landnutzung. Raumforsch Raumordn 72(3):195–209. https://doi.org/10.1007/s13147-014-0278-7

Lambin EF, Gibbs HK, Ferreira L, Grau R, Mayaux P, Meyfroidt P, Morton DC, Rudel TK, Gasparri I, Munger J (2013) Estimating the world’s potentially available cropland using a bottom-up approach. Glob Environ Chang 23(5):892–901. https://doi.org/10.1016/j.gloenvcha.2013.05.005

Lamichhane JR, Aubertot J-N, Begg G, Birch ANE, Boonekamp P, Dachbrodt-Saaydeh S, Hansen JG, Hovmøller MS, Jensen JE, Jørgensen LN, Kiss J, Kudsk P, Moonen A-C, Rasplus J-Y, Sattin M, Streito J-C, Messéan A (2016) Networking of integrated pest management: a powerful approach to address common challenges in agriculture. Crop Prot 89:139–151. https://doi.org/10.1016/j.cropro.2016.07.011

Larkin RP (2015) Soil health paradigms and implications for disease management. Annu Rev Phytopathol 53(1):199–221. https://doi.org/10.1146/annurev-phyto-080614-120357

Last L, Buchmann N, Gilgen AK, Grant M, Shreck A (2015) Foresight study: research for a sustainable Swiss food system. ETH Zürich, Zürich

Laurance WF, Sayer J, Cassman KG (2014) Agricultural expansion and its impacts on tropical nature. Trends Ecol Evol 29(2):107–116. https://doi.org/10.1016/j.tree.2013.12.001

Le QB, Nkonya E, Mirzabaev A (2016) Biomass productivity-based mapping of global land degradation hotspots. In: Nkonya E, Mirzabaev A, von Braun J (eds) Economics of land degradation and improvement—a global assessment for sustainable development. Springer International Publishing, Cham, pp 55–84. https://doi.org/10.1007/978-3-319-19168-3_4

Liebisch F, Pfeifer J, Khanna R, Lottes P, Stachniss C, Falck T, Sander S, Siegwart R, Walter A, Galceran E (2016) Flourish—a robotic approach for automation in crop management. Paper presented at the 22. Workshop Computer-Bildanalyse und Unbemannte autonom fliegende Systeme in der Landwirtschaft. 21.04.2016, Hochschule Harz, Wernigerode. http://www.ipb.uni-bonn.de/wp-content/papercite-data/pdf/liebisch16cbaws.pdf. Accessed 10 Oct 2016

Lin BB (2011) Resilience in agriculture through crop diversification: adaptive management for environmental change. Bioscience 61(3):183–193. https://doi.org/10.1525/bio.2011.61.3.4

Long SP, Karp A, Buckeridgec MS, Davisd SC, Jaiswala D, Mooree PH, Moosea SP, Murphyf DJ, Onwona-Agyemang S, Vonshakh A (2015) Feedstocks for biofuels and bioenergy. In: Mendes Souza C, Victoria RL, Joly CA, Verdade LM (eds) Bioenergy and sustainablitiy: bridging the gaps. SCOPE 72. Scientific Committee on Problems of the Environment (SCOPE), Paris, pp 302–346

Lorenz K, Lal R (2005) The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. In: Advances in agronomy, vol 88. Academic Press, Cambridge, pp 35–66. https://doi.org/10.1016/S0065-2113(05)88002-2

Lorenz K, Lal R (2014) Soil organic carbon sequestration in agroforestry systems. A review. Agron Sustain Dev 34(2):443–454. https://doi.org/10.1007/s13593-014-0212-y

Lorenz M, Brunotte J, Vorderbrügge T, Brandhuber R, Koch HJ, Senger M, Fröba N, Löpmeier F-J (2016) Anpassung der Lasteinträge landwirtschaftlicher Maschinen an die Verdichtungsempfindlichkeit des Bodens - Grundlagen für ein bodenschonendes Befahren von Ackerland. Landbauforsch Appl Agric For Res 66(2):101–144. https://doi.org/10.3220/LBF1473334823000

Lynne GD, Shonkwiler JS, Rola LR (1988) Attitudes and farmer conservation behavior. Am J Agric Econ 70(1):12–19. https://doi.org/10.2307/1241971

Marahrens S, Schmidt S, Frauenstein J, Mathews J, Bussian B-M, Penn-Bressel G, Utermann J, Eberhardt E, Freibauer A, Bechthold M, Tiemeyer B, Wellbrock N, Böttcher F, Glante F (2015) Bodenzustand in Deutschland. Zum "Internationalen Jahr des Bodens". Umweltbundesamt, Dessau-Roßlau

Mauser W, Klepper G, Zabel F, Delzeit R, Hank T, Putzenlechner B, Calzadilla A (2015) Global biomass production potentials exceed expected future demand without the need for cropland expansion. Nat Commun 6. https://doi.org/10.1038/ncomms9946

mb (2016) Kleine Flieger kommen groß raus. top agrar, vol 7. Landwirtschaftsverlag GmbH, Münster

McDaniel MD, Tiemann LK, Grandy AS (2014) Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol Appl 24(3):560–570. https://doi.org/10.1890/13-0616.1

Médiène S, Valantin-Morison M, Sarthou J-P, de Tourdonnet S, Gosme M, Bertrand M, Roger-Estrade J, Aubertot J-N, Rusch A, Motisi N, Pelosi C, Doré T (2011) Agroecosystem management and biotic interactions: a review. Agron Sustain Dev 31(3):491–514. https://doi.org/10.1007/s13593-011-0009-1

Meuli K (2016) EcoRobotix, Terranimo & Cie. environnement, vol 3. NZZ Fachmedien AG, Saint-Gall

Ministère de l'Agriculture dlAedlF (2015/2016) 4 pour 1000. Partners. http://4p1000.org/partners. Accessed 16 Feb 2016

Mitter H, Heumesser C, Schmid E (2015) Spatial modeling of robust crop production portfolios to assess agricultural vulnerability and adaptation to climate change. Land Use Policy 46:75–90. https://doi.org/10.1016/j.landusepol.2015.01.010

Montag D, Everding W, Malms S, Pinnekamp J, Reinhardt J, Fehrenbach H, Arnold U, Trimborn M, Goldbach H, Klett W, Lammers T (2015) Maßnahmen einer weitergehenden Phosphorrückgewinnung aus relevanten Stoffströmen sowie zum effizienten Phosphoreinsatz. UBA Texte 98/2015. Umweltbundesamt, Dessau-Roßlau

Montanarella L (2015) Govern our soils. Nature 528(3 December 2015): 32–33. https://doi.org/10.1038/528032a

Morrison B, Golden JS (2015) An empirical analysis of the industrial bioeconomy: implications for renewable resources and the environment. Bioresources 10(3):4411–4440

Münch T, Berg M, Mirschel W, Wieland R, Nendel C (2014) Considering cost accountancy items in crop production simulations under climate change. Eur J Agron 52(Part A):57–68. https://doi.org/10.1016/j.eja.2013.01.005

Musshoff O (2012) Growing short rotation coppice on agricultural land in Germany: a real options approach. Biomass Bioenergy 41:73–85. https://doi.org/10.1016/j.biombioe.2012.02.001

Naïo Technologies (2016a) Frequently Asked Questions. Naïo Technologies. http://www.naio-technologies.com/en/frequently-asked-questions-faq/#origine. Accessed 15 Jun 2016

Naïo Technologies (2016b) Large-scale vegetable weeding robot - in progress. Naïo Technologies. http://www.naio-technologies.com/en/agricultural-equipment/large-scale-vegetable-weeding-robot/. Accessed 14 Sept 2016

Nendel C, Kersebaum KC, Mirschel W, Wenkel KO (2014) Testing farm management options as climate change adaptation strategies using the MONICA model. Eur J Agron 52(Part A):47–56. https://doi.org/10.1016/j.eja.2012.09.005

Nerlich K, Graeff-Hönninger S, Claupein W (2013) Agroforestry in Europe: a review of the disappearance of traditional systems and development of modern agroforestry practices, with emphasis on experiences in Germany. Agrofor Syst 87(2):475–492. https://doi.org/10.1007/s10457-012-9560-2

Norris PE, Batie SS (1987) Virginia farmers' soil conservation decisions: an application of tobit analysis. J Agric Appl Econ 19(01):79–90. https://doi.org/10.1017/S0081305200017404

Odening M, Brümmer B, von Cramon-Taubadel S, Mußhoff O, Qaim M, Spiller A, Theuvsen L, Hüttel S, Uehleke R (2016) Wiedereinführung der Milchquote kein sinnvolles Instrument der Agrarpolitik. Agra-Europe, vol 24/16

OECD (2009) The bioeconomy to 2030. Designing a policy agenda. Organization for Economic Cooperation and Development. OECD, Paris

Offermann F, Banse M, Deblitz C, Gocht A, Gonzalez-Mellado A, Kreins P, Marquardt S, Osterburg S, Pelikan J, Rösemann C, Salamon P, Sanders J (2016) Thünen-Baseline 2015–2025: Agrarökonomische Projektionen für Deutschland. Thünen Report 40. Johann Heinrich von Thünen-Institut, Braunschweig. https://doi.org/10.3220/REP1458557428000

Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34(2):96–112. https://doi.org/10.1016/j.eja.2010.11.003

Orgiazzi A, Panagos P, Yigini Y, Dunbar MB, Gardi C, Montanarella L, Ballabio C (2016) A knowledge-based approach to estimating the magnitude and spatial patterns of potential threats to soil biodiversity. Sci Total Environ 545–546:11–20. https://doi.org/10.1016/j.scitotenv.2015.12.092

Paris Agreement (2015) Paris agreement, Paris, 12 December 2015, C.N.63.2016.TREATIES-XXVII.7.d of 16 February 2016 (Opening for signature). https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&lang=en

Parker JS, Moore R, Weaver M (2007) Land tenure as a variable in community based watershed projects: some lessons from the Sugar Creek watershed, Wayne and Holmes counties, Ohio. Soc Nat Resour 20(9): 815–833. https://doi.org/10.1080/08941920701460283

Pe'er G, Zinngrebe Y, Hauck J, Schindler S, Dittrich A, Zingg S, Tscharntke T, Oppermann R, Sutcliffe L, Sirami C, Schmidt J, Hoyer C, Schleyer C, Lakner S (2016) Adding some green to the greening: improving the EU's ecological focus areas for biodiversity and farmers. Conserv Lett 10(5):517–530. https://doi.org/10.1111/conl.12333

Pelzer E, Hombert N, Jeuffroy M-H, Makowski D (2014) Meta-analysis of the effect of nitrogen fertilization on annual cereal–legume intercrop production. Agron J 106(5):1775–1786. https://doi.org/10.2134/agronj13.0590

Peters K, Gerowitt B (2014) Important maize weeds profit in growth and reproduction from climate change conditions represented by higher temperatures and reduced humidity. J Appl Bot Food Qual 87. https://doi.org/10.5073/jabfq.2014.087.033

Peters K, Breitsameter L, Gerowitt B (2014) Impact of climate change on weeds in agriculture: a review. Agron Sustain Dev 34(4):707–721. https://doi.org/10.1007/s13593-014-0245-2

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

Popp J, Lakner Z, Harangi-Rákos M, Fári M (2014) The effect of bioenergy expansion: food, energy, and environment. Renew Sust Energ Rev 32:559–578. https://doi.org/10.1016/j.rser.2014.01.056

Popp J, Peto K, Jambor A (2015) Cap 2013 reform: consistency between agricultural challenges and measures. APSTRACT 9(3):47–56. 10.19041/APSTRACT/2015/3/7

Postma-Blaauw MB, de Goede RGM, Bloem J, Faber JH, Brussaard L (2010) Soil biota community structure and abundance under agricultural intensification and extensification. Ecology 91(2):460–473. https://doi.org/10.1890/09-0666.1

Powlson DS, Stirling CM, Jat ML, Gerard BG, Palm CA, Sanchez PA, Cassman KG (2014) Limited potential of no-till agriculture for climate change mitigation. Nat Clim Chang 4(8):678–683. https://doi.org/10.1038/nclimate2292

Prager K, Curfs M (2016) Using mental models to understand soil management. Soil Use Manag 32(1):36–44. https://doi.org/10.1111/sum.12244

Preuße T (2016) Erntetechnik. Größe ist nicht alles. DLG-Mitteilungen, vol 2016. Deutsche Landwirtschafts-Gesellschaft, Frankfurt/Main

Prokopy LS, Floress K, Klotthor-Weinkauf D, Baumgart-Getz A (2008) Determinants of agricultural best management practice adoption: evidence from the literature. J Soil Water Conserv 63(5):300–311. https://doi.org/10.2489/jswc.63.5.300

Quinn LD, Straker KC, Guo J, Kim S, Thapa S, Kling G, Lee DK, Voigt TB (2015) Stress-tolerant feedstocks for sustainable bioenergy production on marginal land. BioEnergy Res 8(3):1081–1100. https://doi.org/10.1007/s12155-014-9557-y

Rasmann S, Bennett A, Biere A, Karley A, Guerrieri E (2017) Root symbionts: powerful drivers of plant above—and belowground indirect defenses. Insect Sci. https://doi.org/10.1111/1744-7917.12464

Ray DK, Ramankutty N, Mueller ND, West PC, Foley JA (2012) Recent patterns of crop yield growth and stagnation. Nat Commun 3:1293. https://doi.org/10.1038/ncomms2296

Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are insufficient to double global crop production by 2050. PLoS One 8(6): e66428. https://doi.org/10.1371/journal.pone.0066428

Reckling M (2016) Leguminosen in neuem Licht. ÖKOLOGIE & LANDBAU 03(2016):47–48

Reckling M, Bergkvist G, Watson CA, Stoddard FL, Zander PM, Walker RL, Pristeri A, Toncea I, Bachinger J (2016) Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. Front Plant Sci 7(669). https://doi.org/10.3389/fpls.2016.00669

Redaktion DLG-Mitteilungen (2016) Sind jetzt die Azole dran? DLG-Mitteilungen Deutsche Landwirtschafts-Gesellschaft, Frankfurt/Main

REN21 (2013) Renewables 2013. Global status report. Key findings 2013. REN, Paris

REN21 (2015) Renewables 2015. Global status report. REN, Paris

Ribeiro A, Fernandez-Quintanilla C, Dorado J, López-Granados F, Peña JM, Rabatel G, Pérez-Ruiz M, Conesa-Muñoz J, Santos PGD (2015) A fleet of aerial and ground robots: a scalable approach for autonomous site-specific herbicide application. Precis Agric 15: 167–173:153-159. https://doi.org/10.3920/978-90-8686-814-8_20

Richard TL, El-Lakany H (2015) Agriculture and forestry integration. In: Mendes Souza C, Victoria RL, Joly CA, Verdade LM (eds) Bioenergy and sustainablitiy: bridging the gaps. SCOPE 72. Scientific Committee on Problems of the Environment (SCOPE), Paris, pp 468–489

Richerzhagen D, Racca P, Zeuner T, Kuhn C, Falke K, Kleinhenz B, Hau B (2011) Impact of climate change on the temporal and regional occurrence of *Cercospora* leaf spot in lower saxony. J Plant Dis Prot 118(5):168–177. https://doi.org/10.1007/bf03356400

Riediger J, Breckling B, Svoboda N, Schröder W (2016) Modelling regional variability of irrigation requirements due to climate change in Northern Germany. Sci Total Environ 541:329–340. https://doi.org/10.1016/j.scitotenv.2015.09.043

Rowbot Systems (2016) Rowbot. http://rowbot.com/. Accessed 15 Jun 2016

Saia S, Rappa V, Ruisi P, Abenavoli MR, Sunseri F, Giambalvo D, Frenda AS, Martinelli F (2015a) Soil inoculation with symbiotic microorganisms promotes plant growth and nutrient transporter genes expression in durum wheat. Front Plant Sci 6:815. https://doi.org/10.3389/fpls.2015.00815

Saia S, Ruisi P, Fileccia V, Di Miceli G, Amato G, Martinelli F (2015b) Metabolomics suggests that soil inoculation with arbuscular mycorrhizal fungi decreased free amino acid content in roots of durum wheat grown under N-limited, P-rich field conditions. PLoS One 10(6):e0129591. https://doi.org/10.1371/journal.pone.0129591

Sang X, Wang D, Lin X (2016) Effects of tillage practices on water consumption characteristics and grain yield of winter wheat under different soil moisture conditions. Soil Tillage Res 163:185–194. https://doi.org/10.1016/j.still.2016.06.003

Schindler HR, Gunashekar S, Cave J, Shahin J, Rhydderch A, Meyer T, Cave B, Lichten C, van der Meulen N, Horvath V, Sousa SER (2014) Foresight services to support strategic programming within horizon 2020. European Commission, Brussels http://hdl.handle.net/11245/1.445041. Accessed 10 Jun 2016

Schjønning P, van den Akker JJH, Keller T, Greve MH, Lamandé M, Simojoki A, Stettler M, Arvidsson J, Breuning-Madsen H (2015) Driver-pressure-state-impact-response (DPSIR) analysis and risk assessment for soil compaction—a European perspective. In: Donald LS (ed) Advances in agronomy, vol 133. Academic Press, Cambridge, pp 183–237. https://doi.org/10.1016/bs.agron.2015.06.001

Schleyerbach (2009) agriMA 2009 Strukturen – Typologien - Medien. Paper presented at the Agrar-Medientage Münster, 28–29 April 2009. http://www.agrima2009.de/Bilder/agriMAPraesentationSchleyerbach.pdf Accessed 15 Sept 2016

Schmidhalter U, Maidl F-X, Heuwinkel H, Demmel M, Auernhammer H, Noack P, Rothmund M (2008) Precision farming—adaptation of land use management to small scale heterogeneity. In: Schröder P, Pfadenhauer J, Munch JC (eds) Perspectives for agroecosystem management. Elsevier, Amsterdam, pp 121–199. https://doi.org/10.1016/B978-044451905-4.50007-6

Schorling M, Enders C, Voigt CA (2015) Assessing the cultivation potential of the energy crop *Miscanthus* × *giganteus* for Germany. GCB Bioenergy 7(4):763–773. https://doi.org/10.1111/gcbb.12170

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 Pol 38:45–58. https://doi.org/10.1016/j.envsci.2013.10.002

Science for Environment Policy (2016) Synthetic biology and bidiversity. Future Brief 15. Produced for the European Commission DG Environment by the Science Communication Unit. UWE, Bristol. Accessed 14 Jul 2017

Sklenicka P, Molnarova KJ, Salek M, Simova P, Vlasak J, Sekac P, Janovska V (2015) Owner or tenant: who adopts better soil conservation practices? Land Use Policy 47:253–261. https://doi.org/10.1016/j.landusepol.2015.04.017

Smeets E, Weterings R (1999) Environmental indicators: typology and overview. Technical Report No. 25. European Environment Agency, Copenhagen. www.eea.europa.eu/publications/TEC25/download. Accessed 14 Apr 2016

Smit B, Smithers J (1992) Adoption of soil conservation practices: an empirical analysis in Ontario, Canada. Land Degrad Dev 3(1):1–14. https://doi.org/10.1002/ldr.3400030102

Smith J, Pearce BD, Wolfe MS (2013) Reconciling productivity with protection of the environment: is temperate agroforestry the answer?

Renewable Agric Food Syst 28(1):80–92. https://doi.org/10.1017/S1742170511000585

Smith P, House JI, Bustamante M, Sobocká J, Harper R, Pan G, West PC, Clark JM, Adhya T, Rumpel C, Paustian K, Kuikman P, Cotrufo MF, Elliott JA, McDowell R, Griffiths RI, Asakawa S, Bondeau A, Jain AK, Meersmans J, Pugh TAM (2016) Global change pressures on soils from land use and management. Glob Chang Biol 22(3):1008–1028. https://doi.org/10.1111/gcb.13068

Soule MJ, Tegene A, Wiebe KD (2000) Land tenure and the adoption of conservation practices. Am J Agric Econ 82(4):993–1005. https://doi.org/10.1111/0002-9092.00097

Statistisches Bundesamt (2010) Bodenbearbeitung, Bewässerung, Landschaftselemente - Erhebung über landwirtschaftliche Produktionsmethoden (ELPM) - Fachserie 3 Heft 5–2010. Statistisches Bundesamt, Wiesbaden

Statistisches Bundesamt (2011) Fachserie 3 Heft 1. Land und Forstwirtschaft, Fischerei. Landwirtschaftliche Berufsbildung der Betriebsleiter/Geschäftsführer. Landwirtschaftszählung/Agrarstrukturerhebung 2010. Statistisches Bundesamt, Wiesbaden

Statistisches Bundesamt (2014a) Fachserie 3 Reihe 2.1.6. Land und Forstwirtschaft, Fischerei. Eigentums- und Pachtverhältnisse. Agrarstrukturerhebung. Statistisches Bundesamt, Wiesbaden

Statistisches Bundesamt (2014b) Fachserie 3 Reihe 2.1.8. Land und Forstwirtschaft, Fischerei. Arbeitskräfte. Agrarstrukturerhebung. Statistisches Bundesamt, Wiesbaden

Statistisches Bundesamt (2014c) Land und Forstwirtschaft, Fischerei. Bewässerung in landwirtschaftlichen Betrieben / Agrarstrukturerhebung. Statistisches Bundesamt, Wiesbaden

Statistisches Bundesamt (2016a) Fachserie 3 Reihe 3.1.2 Land und Forstwirtschaft, Fischerei. Landwirtschaftliche Bodennutzung. Anbau auf dem Ackerland (Vorbericht). Statistisches Bundesamt, Wiesbaden

Statistisches Bundesamt (2016b) Feldfrüchte und Grünland. Statistisches Bundesamt, Wiesbaden. https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/LandForstwirtschaftFischerei/FeldfruechteGruenland/Tabellen/AckerlandHauptfruchtgruppenFruchtarten.html. Accessed 14 Oct 2016

Steidl J, Schuler J, Schubert U, Dietrich O, Zander P (2015) Expansion of an existing water management model for the analysis of opportunities and impacts of agricultural irrigation under climate change conditions. Water 7(11):6351–6377. https://doi.org/10.3390/w7116351

Stolarski MJ, Krzyżaniak M, Łuczyński M, Załuski D, Szczukowski S, Tworkowski J, Gołaszewski J (2015) Lignocellulosic biomass from short rotation woody crops as a feedstock for second-generation bioethanol production. Ind Crop Prod 75(Part B):66–75. https://doi.org/10.1016/j.indcrop.2015.04.025

Stone D, Blomkvist P, Hendriksen NB, Bonkowski M, Jørgensen HB, Carvalho F, Dunbar MB, Gardi C, Geisen S, Griffiths R, Hug AS, Jensen J, Laudon H, Mendes S, Morais PV, Orgiazzi A, Plassart P, Römbke J, Rutgers M, Schmelz RM, Sousa JP, Steenbergen E, Suhadolc M, Winding A, Zupan M, Lemanceau P, Creamer RE (2016) A method of establishing a transect for biodiversity and ecosystem function monitoring across Europe. Appl Soil Ecol 97:3–11. https://doi.org/10.1016/j.apsoil.2015.06.017

Stoorvogel JJ, Kooistra L, Bouma J (2015) Managing soil variability at different spatial scales as a basis for precision agriculture. Soil specific farming. Precision agriculture. CRC Press, Boca Raton doi: https://doi.org/10.1201/b18759-3,

Teagasc (2016) Taegasc Technology Foresight 2035. Technology transforming Irish agri-food and bioeconomy. Teagasc, Carlow. http://www.teagasc.ie/publications/2016/3897/Teagasc-Technology-Foresight-Report-2035.pdf. Accessed 27 Jun 2016

Techen A-K (2015) Ergebnisse der standardisierten Landwirte-Befragung. In: Techen A-K, Ries E, Steinführer A (eds) Evaluierung der Gewässerschutzberatung in Hessen im Kontext der EU-Wasserrahmenrichtlinie: Auswirkungen auf Wissen und Handeln von Landwirten. Thünen-Report 33. Thünen-Institut, Braunschweig, pp 27–104. https://doi.org/10.3220/REP1446716352000

Techen A-K, Ries E, Steinführer A (2015) Evaluierung der Gewässerschutzberatung in Hessen im Kontext der EU-Wasserrahmenrichtlinie: Auswirkungen auf Wissen und Handeln von Landwirten. Thünen-Report 33. Thünen-Institut, Braunschweig. https://doi.org/10.3220/REP1446716352000

Thiele-Bruhn S, Bloem J, de Vries FT, Kalbitz K, Wagg C (2012) Linking soil biodiversity and agricultural soil management. Curr Opin Environ Sustain 4(5):523–528. https://doi.org/10.1016/j.cosust.2012.06.004

Thies JE, Rillig MC, Graber ER (2015) Biochar effects on the abundance, activity and diversity of the soil biota. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science, technology and implementation. Taylor & Francis, Routledge, pp 327–390

Thrän D, Witt J, Schaubach K, Kiel J, Carbo M, Maier J, Ndibe C, Koppejan J, Alakangas E, Majer S, Schipfer F (2016) Moving torrefaction towards market introduction—technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project. Biomass Bioenergy 89:184–200. https://doi.org/10.1016/j.biombioe.2016.03.004

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci U S A 108(50):20260–20264. https://doi.org/10.1073/pnas.1116437108

Tittonell P (2014) Ecological intensification of agriculture—sustainable by nature. Curr Opin Environ Sustain 8:53–61. https://doi.org/10.1016/j.cosust.2014.08.006

Torralba M, Fagerholm N, Burgess PJ, Moreno G, Plieninger T (2016) Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agric Ecosyst Environ 230:150–161. https://doi.org/10.1016/j.agee.2016.06.002

Troost C, Berger T (2015) Dealing with uncertainty in agent-based simulation: farm-level modeling of adaptation to climate change in Southwest Germany. Am J Agric Econ 97(3):833–854. https://doi.org/10.1093/ajae/aau076

Trott H (2010) Grundnährstoffversorgung und Qualität von Grünland. In: VDLUFA VDLU-uF (ed) Kongressband 2010 Kiel. VDLUFA-Schriftenreihe Band 66/2010. VDLUFA-Verlag, Darmstadt, pp 93–106

Tscherning K, Helming K, Krippner B, Sieber S, Paloma SGY (2012) Does research applying the DPSIR framework support decision making? Land Use Policy 29(1):102–110. https://doi.org/10.1016/j.landusepol.2011.05.009

Tsiafouli MA, Thébault E, Sgardelis SP, de Ruiter PC, van der Putten WH, Birkhofer K, Hemerik L, de Vries FT, Bardgett RD, Brady MV, Bjornlund L, Jørgensen HB, Christensen S, Hertefeldt TD, Hotes S, Gera Hol WH, Frouz J, Liiri M, Mortimer SR, Setälä H, Tzanopoulos J, Uteseny K, Pižl V, Stary J, Wolters V, Hedlund K (2015) Intensive agriculture reduces soil biodiversity across Europe. Glob Chang Biol 21(2):973–985. https://doi.org/10.1111/gcb.12752

UNFCCC Secretariat (2015) Synthesis report on the aggregate effect of the intended nationally determined contributions (FCCC/CP/2015/7). UNFCCC Secretariat. http://unfccc.int/resource/docs/2015/cop21/eng/07.pdf. Accessed 12 Apr 2016

United Nations (2015) Transforming Our World: The 2030 Agenda for Sustainable Developoment. A/RES/70/1

United Nations, Department of Economic and Social Affairs, Population Division (2015) World population prospects: the 2015 revision, key findings and advance tables. Working Paper No. ESA/P/WP.241. http://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf. Accessed 4 Apr 2016

Upson MA, Burgess PJ, Morison JIL (2016) Soil carbon changes after establishing woodland and agroforestry trees in a grazed pasture.

Geoderma 283:10–20. https://doi.org/10.1016/j.geoderma.2016.07.002

Valin H, Sands RD, van der Mensbrugghe D, Nelson GC, Ahammad H, Blanc E, Bodirsky B, Fujimori S, Hasegawa T, Havlik P, Heyhoe E, Kyle P, Mason-D'Croz D, Paltsev S, Rolinski S, Tabeau A, van Meijl H, von Lampe M, Willenbockel D (2014) The future of food demand: understanding differences in global economic models. Agric Econ 45(1):51–67. https://doi.org/10.1111/agec.12089

van Grinsven H, Erisman JW, de Vries W, Westhoek H (2015) Potential of extensification of European agriculture for a more sustainable food system, focusing on nitrogen. Environ Res Lett 10(2): 025002. https://doi.org/10.1088/1748-9326/10/2/025002

Van Oost K, Govers G, Desmet P (2000) Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landsc Ecol 15(6):577–589. https://doi.org/10.1023/a:1008198215674

VandenBygaart AJ (2016) The myth that no-till can mitigate global climate change. Agric Ecosyst Environ 216:98–99. https://doi.org/10.1016/j.agee.2015.09.013

Verbruggen E, Kiers ET, Bakelaar PNC, Röling WFM, van der Heijden MGA (2012) Provision of contrasting ecosystem services by soil communities from different agricultural fields. Plant Soil 350(1): 43–55. https://doi.org/10.1007/s11104-011-0828-5

Voigt TB (2015) Are the environmental benefits of *Miscanthus* × *giganteus* suggested by early studies of this crop supported by the broader and longer-term contemporary studies? GCB Bioenergy 7(4):567–569. https://doi.org/10.1111/gcbb.12150

Vollprecht J, Reichelt S, Rühr C, Becker Büttner Held, Holzhammer U, Stelzer M, Hahn H (2015) Fördervorschläge für Biogas-Bestandsanlagen im EEG. Status-quo-Analyse, Reformmodellanalyse und Fördervorschlag. TEXTE 89/2015

Vrebos D, Bampa F, Creamer R, Gardi C, Ghaley B, Jones A, Rutgers M, Sandén T, Staes J, Meire P (2017) The impact of policy instruments on soil multifunctionality in the European Union. Sustainability 9(3):407. https://doi.org/10.3390/su9030407

Watson JEM, Dudley N, Segan DB, Hockings M (2014) The performance and potential of protected areas. Nature 515(7525):67–73. https://doi.org/10.1038/nature13947

Wauters E, Bielders C, Poesen J, Govers G, Mathijs E (2010) Adoption of soil conservation practices in Belgium: an examination of the theory of planned behaviour in the agri-environmental domain. Land Use Policy 27(1):86–94. https://doi.org/10.1016/j.landusepol.2009.02.009

Weiser C, Zeller V, Reinicke F, Wagner B, Majer S, Vetter A, Thraen D (2014) Integrated assessment of sustainable cereal straw potential and different straw-based energy applications in Germany. Appl Energy 114:749–762. https://doi.org/10.1016/j.apenergy.2013.07.016

Weltzien C, Gebbers R (2016) Aktueller Stand der Technik im Bereich der Sensoren für Precision Agriculture. Referate der 36. GIL-Jahrestagung in Osnabrück - Intelligente Systeme - Stand der Technik und neue Möglichkeiten. http://www.gil-net.de/publikationen_autoren.php?id=37&band=28. 8 June 2016

Werner M, Steinmann H-H, Schlatter N, Spiegel H, Wauters E, Ruysschaert G (2014) Farmers' rationality in soil management: which factors ifluence implementation of sustainable management practices in soil conservation?—a case study in Germany and Austria. In: Thomas Aenis AK, Maja-Catrin Riecher, Rebecka Ridder, Heike Schobert, Holger Fischer (ed) Farming systems facing global challenges: capacities and strategies. Proceedings of the 11th European IFSA Symposium 1–4 April 2014 in Berlin, Germany. http://ifsa.boku.ac.at/cms/fileadmin/Proceeding2014/WS_1_1_Werner.pdf. Accessed 29 Jun 2016

Wichmann S (2016) Commercial viability of paludiculture: a comparison of harvesting reeds for biogas production, direct combustion, and thatching. Ecol Eng 103:497–505. https://doi.org/10.1016/j.ecoleng.2016.03.018

Wiesmeier M, Hübner R, Kögel-Knabner I (2015) Stagnating crop yields: an overlooked risk for the carbon balance of agricultural soils? Sci Total Environ 536:1045–1051. https://doi.org/10.1016/j.scitotenv.2015.07.064

Wissenschaftlicher Beirat Agrarpolitik, Ernährung und gesundheitlicher Verbraucherschutz, Wissenschaftlicher Beirat Waldpolitik beim (2016) Klimaschutz in der Land- und Forstwirtschaft sowie den nachgelagerten Bereichen Ernährung und Holzverwendung. Gutachten. http://www.bmel.de/SharedDocs/Downloads/Ministerium/Beiraete/Agrarpolitik/Klimaschutzgutachten_2016.pdf?__blob=publicationFile. Accessed 15 Nov 2016

Wissenschaftlicher Beirat für Agrarpolitik beim BMELV (2010) EU-Agrarpolitik nach 2013. Plädoyer für eine neue Politik für Ernährung, Landwirtschaft und ländliche Räume. Gutachten des Wissenschaftlicher Beirats für Agrarpolitik beim Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz. http://ifsa.boku.ac.at/cms/fileadmin/Proceeding2014/WS_1_1_Werner.pdf. 7 June 2016

Wissenschaftlicher Beirat für Düngungsfragen beim BMELV (2011) Nachhaltiger Umgang mit der begrenzten Ressource Phosphor durch Recycling und Erhöhung der Phosphoreffizienz der Düngung. http://www.bmel.de/SharedDocs/Downloads/Ministerium/Beiraete/Duengungsfragen/Phosphor.pdf?__blob=publicationFile. Accessed 19 Apr 2016

Witzel C-P, Finger R (2016) Economic evaluation of *Miscanthus* production—a review. Renew Sust Energ Rev 53:681–696. https://doi.org/10.1016/j.rser.2015.08.063

Yu Y, Stomph T-J, Makowski D, van der Werf W (2015) Temporal niche differentiation increases the land equivalent ratio of annual intercrops: a meta-analysis. Field Crops Res 184:133–144. https://doi.org/10.1016/j.fcr.2015.09.010

Zander P, Amjath-Babu TS, Preissel S, Reckling M, Bues A, Schläfke N, Kuhlman T, Bachinger J, Uthes S, Stoddard F, Murphy-Bokern D, Watson C (2016a) Grain legume decline and potential recovery in European agriculture: a review. Agron Sustain Dev 36(2):26. https://doi.org/10.1007/s13593-016-0365-y

Zander P, Uthes S, Schläfke N, Neubert J, Hufnagel J, Berger G (2016b) Comparing the greening rules and alternatives with regard to income effects and production pattern. Paper presented at the Jahrestagung der GEWISOLA Agrar- und Ernährungswirtschaft: regional vernetzt und global erfolgreich, Bonn, 28–30 September 2016. http://ageconsearch.umn.edu/bitstream/244861/2/Zander.pdf. Accessed 9 Dec 2016

Zandersen M, Jørgensen SL, Nainggolan D, Gyldenkærne S, Winding A, Greve MH, Termansen M (2016) Potential and economic efficiency of using reduced tillage to mitigate climate effects in Danish agriculture. Ecol Econ 123:14–22. https://doi.org/10.1016/j.ecolecon.2015.12.002

Zhang J-L, Aziz M, Qiao Y, Han Q-Q, Li J, Wang Y-Q, Shen X, Wang S-M, Paré PW (2014) Soil microbe *Bacillus subtilis* (GB03) induces biomass accumulation and salt tolerance with lower sodium accumulation in wheat. Crop Pasture Sci 65(5):423–427. https://doi.org/10.1071/CP13456

Zhang R, Yang H, Gao J, Zhang Y, Wang Z, Fan X, Bi W (2016) Subsoiling facilitating accumulation and transportation of dry matter and phosphorus of spring maize. Trans Chin Soc Agric Eng 32(19): 106–112