Ecological Economics 159 (2019) 291–300

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Towards valuation of biodiversity in agricultural soils: A case for earthworms☆

Elke Plaas[a,b,*], Friederike Meyer-Wolfarth[c,g], Martin Banse[d], Jan Bengtsson[e], Holger Bergmann[b], Jack Faber[f], Martin Potthoff[a], Tania Runge[d], Stefan Schrader[g], Astrid Taylor[e]

[a] Centre of Biodiversity and Sustainable Land Use (CBL), Georg-August University Goettingen, Germany
[b] Department of Agricultural Economics and Rural Development, Georg-August University Goettingen, Germany
[c] Institute for Plant Protection in Field Crops and Grassland, Julius Kühn-Institute, Braunschweig, Germany
[d] Institute of Market Analysis, Johann Heinrich von Thünen-Institute, Braunschweig, Germany
[e] Department of Ecology, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden
[f] Wageningen Environmental Research, Wageningen, the Netherlands
[g] Institute of Biodiversity, Johann Heinrich von Thünen-Institute, Braunschweig, Germany

ARTICLE INFO

Keywords:
Ecosystem services
Soil biodiversity
Economic value
Soil management practices
Sustainability
Ecosystem engineers

ABSTRACT

Soil biodiversity is deteriorating in Europe due to an on-going intensification of agriculture, climate change and food production supporting measures of the European Common Agricultural Policy (CAP). Nevertheless, the CAP tries to take biodiversity into account via proposing a range of agri-environmental measures. These ES contribute to food security, climate change mitigation, water retention and plant biomass growth. Healthy soils also help to prevent erosion, desertification, and landslides and to stabilise crop yields. The provision of ES by soil biota is a result of their impact on soil processes in interaction with soil conditions as well as soil management practices of the farmers such as tillage or crop rotations. Some taxa amongst soil biota play key roles in regulating soil processes. With respect to biocontrol of soil-borne pests, the earthworm species *Lumbricus terrestris* is known to play an important role in suppressing toxigenic plant pathogens, such as *Fusarium culmorum* and its mycotoxin deoxynivalenol (DON). We highlight the importance of earthworms for pest control to conceptualise and show how farmers' management practices influence soil ecosystem services and outline how this can be examined in a socio-ecological context by providing a concrete example of an economical evaluation of ES provided by earthworms.

1. Introduction – why earthworms are worth gold (the worm-value)

Healthy and productive soils are necessary for sustainable food, feed and fibre production worldwide (FAO and ITPS, 2015). Soil biota provide a great variety of ecosystem services (ES) (Barrios, 2007; Wall, 2012) but in spite of this knowledge their importance for e.g. crop production and soil formation is hardly mentioned in central publications such as the Millennium Ecosystem Assessment (MA, 2005) and the UK NEA (2011). In addition, although ES in general are important for human well-being and economic prosperity, the general focus on soil management for yield and production in agriculture has had negative effects on other than provisioning ecosystem services (e.g., Geiger et al., 2010; Power, 2010; UK NEA, 2011), which undermines the long-term sustainability of agricultural practices (Wall, 2012).

In 2015, the UN adopted the 17 Sustainable Development Goals (SDGs) (UN General Assembly, 2015). This ambitious follow-up to the Millennium Development Goals (MDG; UN, 2015) calls on all signatory countries to undertake efforts to achieve the SDGs over the next 15 years and puts a much stronger focus on the sustainable use of natural resources than the MDGs did. For the first time, soil quality was directly targeted in an international commitment (Keesstra et al., 2016), even though it has long been recognised that soils are essential for sustainable development. Although belowground biodiversity is not explicitly mentioned in the SDGs, there is a growing awareness amongst scientists and governments that healthy soils and soil biodiversity are interdependent, and that reductions in soil biodiversity render soils more vulnerable to other degradation processes (Keesstra et al., 2016).

☆ Authors are listed in alphabetical order except for Elke Plaas and Friederike Meyer-Wolfarth as main contributors.

* Corresponding author at: Georg-August University Göttingen, Department of Agricultural Economics and Rural Development, Platz der Göttinger Sieben 5, D-37073 Göttingen, Germany.
E-mail address: elke.plaas@agr.uni-goettingen.de (E. Plaas).

https://doi.org/10.1016/j.ecolecon.2019.02.003
Received 28 March 2018; Received in revised form 30 January 2019; Accepted 5 February 2019

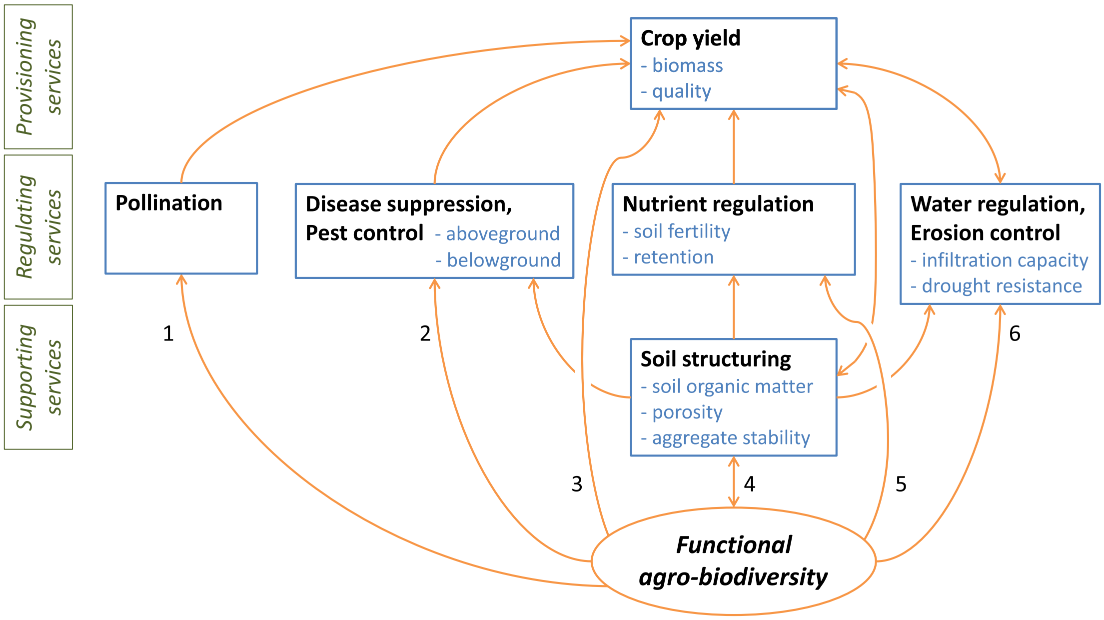

Fig. 1. Potential contributions of functional agrobiodiversity to ecosystem services for agriculture (1) Direct contributions to the crop yield by pollination, mainly by insects, but also mammals and birds, some pollinating insects have below-ground larval stages; (2) biological pest control by parasitism and predation, often by insects which may have below-ground larval stages or use soil animals as alternative prey; disease control by fungi and bacteria, indirectly also by soil animals such as earthworms; (3) nutrient regulation of soils and crops e.g. by nitrogen-fixing bacteria, efficient uptake of nutrients via mycorrhiza; (4) formation of favourable soil structure by mycorrhiza and other fungi, bacteria, earthworms and other soil animals; aeration and creation of soil pores by burrowing soil animals allows easy soil penetration and growth of plant roots (5) decomposition and mobilisation and immobilisation of nutrients by microorganisms decomposing organic matter and mineralizing nutrients, processes which are mediated by soil animals (e.g. via bioturbation, litter fragmentation and translocation of plant remains); (6) anecic and litter-dwelling earthworms regulate soil water-drainage and moisture holding capacity. Double sided arrows indicate mutual dependency of services; these may result in synergies or trade-offs.
(Redrawn from Faber et al. (2016).)

The strong connection between soil quality and food provision is made visible in SDG 2 on food security, which says that by 2030 sustainable food production systems should be insured by implementing resilient agriculture practices that improve soil quality.

Here we highlight the importance of soil biota for ecosystem processes, ecosystem services, food production and human well-being. We explicitly focus on ES mediated by earthworms because earthworms are usually the most abundant soil animal group in agricultural soils in terms of biomass and therefore affect many ES including soil structure and quality as well as plant production (e.g. Clements et al., 1991; Van Groeningen et al., 2014; Bertrand et al., 2015a). In addition, they are one of the few soil animal groups that farmers as well as the general public are aware of and care about. For reasons of simplification and communication of the value and benefits of earthworms for farming systems and societies, we focus on the role this group plays for the suppression of toxigenic fungal plant pathogens producing mycotoxins. We have chosen this example because in the European Union (EU), toxigenic plant pathogens cause severe economic losses every year. In particular, *Fusarium* species are amongst the most relevant pathogens in cereals. The main host plants are wheat, triticale and maize and to a lower extent other winter cereals. In 2015, more than two thirds (68%) of the EU cropland were grown with crops susceptible to a *Fusarium* infection (Eurostat, 2017).

2. Towards an economic value for sustainable agriculture: the importance of soil organisms for ecosystem services

Ongoing land degradation and environmental incidents such as severe droughts constantly show that we cannot take nature's benefits for granted. Fresh water supply or air quality regulation cannot be seen as unrestrained public goods. In particular, in times of scarcity or absence of resources, the importance of providing ES becomes apparent. Therefore, in accordance with welfare economics theory, we assume that an economic valuation can provide useful information about changes resulting from the management of organisms that directly affect ES, such as the soil biota.

Although the notion that humans depend on nature for their well-being has been recognised for a long time (see e.g. Gomez-Baggethun et al., 2010), the formulation of this as ES is more recent. In two formative articles, ES were defined as “the conditions and processes through which natural ecosystems and the species that make them up, sustain and fulfil human life” (Daily, 1997) or as “the benefits human populations derive directly or indirectly from ecosystem functions” (Costanza et al., 1997). The subtle differences between these definitions illustrate that the term ES can be approached by a basically ecological as well as a more economic perspective. Costanza et al. (2017) provide a concise summary of the progress of bringing environmental facts into the economic debate that has been made since two decades of research. However, the use of the ES concept has not been prominent in agricultural sciences (Tancoigne et al., 2015). It was argued that agricultural sciences mainly address ES in a biophysical manner, and often use other but similar concepts (Tancoigne et al., 2015).

ES have been characterised as being the outcome of actions and interactions of organisms (e.g. Bengtsson, 2010), which result in primary or secondary production of plants and animals used by humans, pollination of crops, or biological control of pests. However, in production ecosystems, such as those in agriculture, ecosystem processes are not the only determinant of ES. The ES such as crop yield are co-produced by ecosystem processes and by the management of the agro-ecosystem (Rist et al., 2014; Bengtsson, 2015; Palomo et al., 2016). This makes it necessary to understand and explicitly include in the ES concept the largely socio-economic processes that determine how farmers manage their land, and how this affects the delivery of ES to farmers and other stakeholders in society. How farmers could reduce the

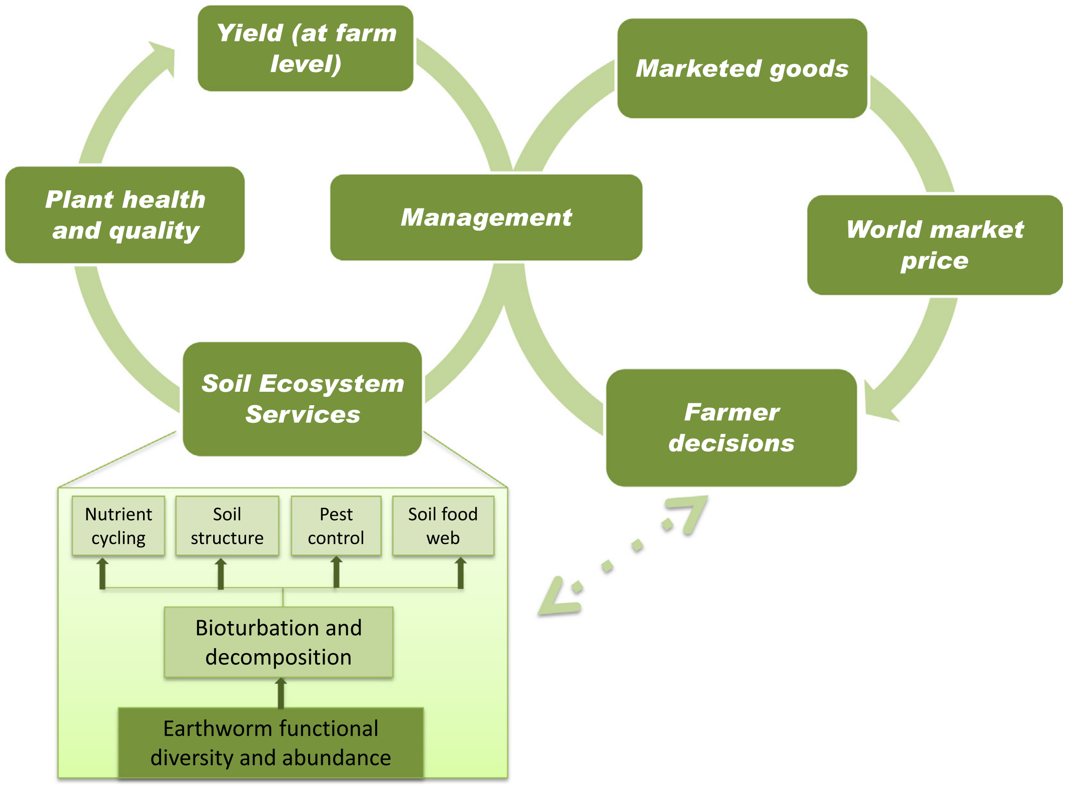

Fig. 2. Conceptual model for understanding the linkage between soil ecology and biodiversity and economy through soil management practices, with earthworms as an example.

fungicide treatment with the support of earthworms can be seen in an example provided in Section 4.

Apart from genetic diversity in crops and cattle, biodiversity per se has often been considered of little consequence for agriculture in agronomy. However, there are certain groups of organisms that are, or can be, especially useful in support of agricultural production systems. These organisms can be termed 'functional agro-biodiversity' (FAB) (ELN-FAB, 2012; Faber et al., 2016) and include natural predators on pests, pollinators and mycorrhizal plant symbionts. While ecological research has provided an increasing body of evidence of such "biological cultivation support" for some decades, ecological research is currently validating how to optimise FAB in adaptive management systems.

Five main regulating and supporting services to agriculture and farming can be distinguished (Fig. 1): Pollination, disease suppression and pest control, nutrient regulation, water regulation and erosion control as well as soil structuring. Each of these ES depends on healthy soils and diverse soil organism communities. Many pollinator insects conclude their reproduction cycle belowground, including egg deposition and larval development. Most microbial antagonists to fungal and bacterial crop diseases and animal pests are also soil-borne, as are many natural predators that operate as biological pest control agents aboveground. Soils therefore represent an essential habitat in the agro-ecosystem on which FAB depends heavily. As a consequence, soil management by the farmer needs to address the soil as a habitat as well as a substrate for cropping, in order to optimise the services that FAB provides for farmers' financial interest, and to ensure long-term sustainability of soil fertility, soil structure, and ES.

Farmers, landowners and agricultural businesses may be motivated to make a transition towards increasing use of sustainable practices to enhance ES provisioning for several reasons:

First of all, conventional agriculture (CA) is increasingly facing threats from soil degradation, such as compaction, erosion, organic matter decline, and soil biodiversity loss. The European Commission (2006a) identified these threats in the proposal for a Soil Framework Directive, which was finally withdrawn in May 2014 (for background and reasons see Glaesner et al., 2014). These threats are already stabilising maximum yields at current levels despite increased management efficiency, and can be expected to further impact food production and the economy of agronomical businesses by gradually reducing crop yields and quality (farmers' profitable income) as well as an erosion of buffering capacity to future increased incidences of extreme events affecting agriculture, e.g. heavy rainfall, droughts, or heatwaves that may cause partial or complete crop loss (farmers' income security) (Collaku and Harrison, 2002).

Secondly, under the European Common Agricultural Policy (CAP) regulations farmers are encouraged to include practices that involve 'ecological intensification'. Depending on CAP instruments being developed and evaluated, and depending on specific implementation by Member States, CAP payments for 'greening agriculture' measures may increase the application of farming practices that help to close nutrient cycles (cover crops, green fertilizers, organic manure) and decrease land use intensity (reduced tillage, multiple-crop rotations cycles including grasses/cereals) (Van Doorn et al., 2017). These measurements are likely to increase soil biodiversity in general. But we are looking inside the complexity to find out more about useful tools to stimulate soil biota for healthy soils with farm management options.

Thirdly, bringing together the interests of farming and nature conservation may result in 'nature inclusive agriculture'. With the second pillar of the common agricultural policy (CAP), the EU's rural development policy is designed to support rural areas and meet the wide range of economic, environmental and societal challenges in the member countries. CAP Pillar II instruments could be developed to promote farming measures that aim to conserve and enhance aboveground biodiversity (e.g. game crops, set-aside, and wildlife seed mixtures, fallow land, field margins and flower strips, beetle banks, wood shingles and other green veins in the landscape). These interventions will also enhance natural enemies for pest control as well as provide habitat for wild pollinators (insects, birds and mammals). Also, indirectly, soil biodiversity in agricultural fields will profit from these measures as the surrounding landscape elements provide opportunity for recolonization after disturbances from tillage (Frazao et al., 2017) or extreme weather events.

Reason 1 above suggests that conventional agriculture without fundamental production innovations directed towards avoiding harmful management practices risks leads to a dead end. In that case, an agricultural system transition is needed to guarantee future sustainability in farming. Reasons 2 and 3 provide perspectives for such a transition and propose some subsidiary support measures that could contribute to the transition costs.

Soil management can be seen as the link between the on-farm cycle where soil biota mediated processes affect plant health and yield and the local or global cycle of crop production and trade on global markets (Fig. 2). This highlights management by farmers as a key process linking ES to the economy of the food system.

Agricultural soil management practices affect biological activity, soil ES, and also disservices such as soil-borne pests and pathogens. The provision of ES through soil and crop management is a result of interactions between soil biota and the abiotic soil environment in what has for a long time been called as a 'black box' underground. Within this 'black box' different functional groups of soil biota are closely linked within a metabolic or feeding network, the soil food web (Fig. 3): *Chemical engineers* are responsible for the decomposition of plant organic matter into nutrients readily available for plants, animals and humans. *Biological regulators* modulate populations of soil organisms through grazing, predation or parasitism including pests and diseases. *Ecosystem engineers* modify environmental conditions for other organisms through their mechanical activities (Jones et al., 1994; Lavelle et al., 1997; Turbé et al., 2010). This functional classification provides a clear framework for innovative farm management options to stimulate soil biodiversity.

In this paper, we focus on a selected set of ES that are strongly related to the abundance and functional diversity of earthworms and agricultural management. To link these processes to the economy cycle in Fig. 2, we consider that ES that are supplied and consumed in the absence of market transactions can be identified as a form of positive externalities within the neoclassical economic paradigm.

From the economic point of view there is no well-qualified answer to the question: "What is the economic value of ES provided by earthworms"? In an attempt to categorise values of biodiversity, Bengtsson et al. (1997) distinguished between an instrumental value of direct importance for a system and an insurance value indirectly maintaining functioning and sustainability of a system. Decaëns et al. (2006) differentiated between the intrinsic values of species without any economic relevance and instrumental values of species with economic relevance. The latter were subdivided into direct economic values, when species are for instance harvested for food or feed usage, and indirect economic values derived from biological activity driving ecological processes and providing ES thereby (Decaëns et al., 2006). Accordingly, the activities of earthworms in their multiple roles (sensu Turbé et al., 2010) as ecosystem engineers forming soil structure, as chemical engineers decomposing organic residues and as biological regulators affecting other soil organisms, such as reducing soil-borne pathogens, can be assigned to indirect economic values. An economic assessment of earthworm services would provide strong arguments to convince policy makers to work more actively towards the protection of the soil system

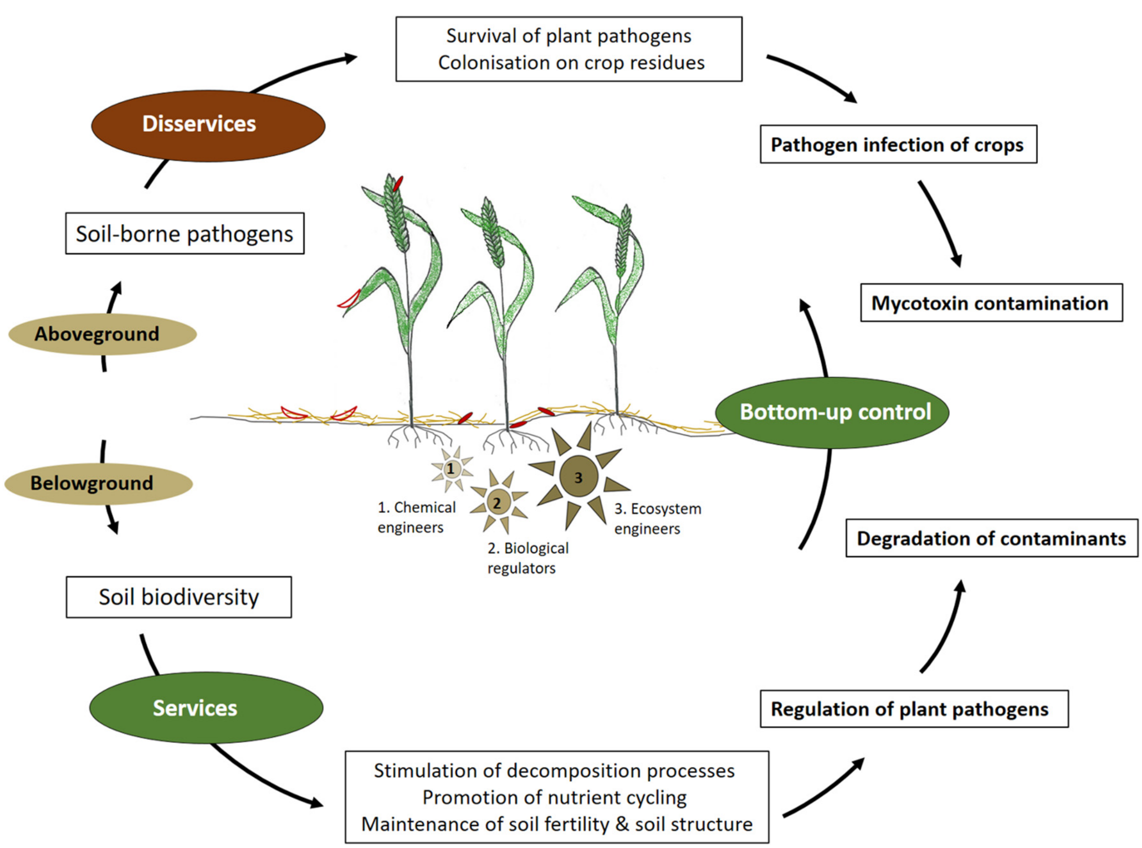

Fig. 3. Ecosystem services and disservices provided by soil organisms in agroecosystems. Increased disease pressure of fungal plant pathogens under conservation agriculture may lead to higher infection rates in crops. Whereas metabolic interactions of different functional groups (chemical engineers, biological regulators and ecosystem engineers, after Turbé et al., 2010) of the soil biodiversity pool result in the provision of ecosystem services and a bottom-up control and compensate for the infection risk.
(Modified after Meyer-Wolfarth (2016).)

Table 1
Direct inhibitory effects of different earthworm species within different functional traits (detritivorous, geophagous) on fungal plant pathogens on wheat (wheat plant, wheat straw), considering the individual density of earthworms [Ind m^{-2}], the soil provided in the experiments and the experimental conditions (climate chamber, greenhouse, field) within an experimental time span of 3–17 weeks. The reduction [%] refers to a direct effect on disease severity or fungal biomass as defined in the according reference. The effects were observed compared to a non-earthworm control.

Earth-worm species	Feeding trait	[Ind m^{-2}]	Plant pathogen	Reduction [%]	Effect	Soil	Condition	Reference
A. t.	Geophagous	471	*Rhizoctonia solani*	45	Reduced root disease rating[a]	Loam fine sandy	Climate chamber	Stephens et al. (1993)
A. t.	Geophagous	471	*Rhizoctonia solani*	40	Reduced root disease rating[a]	Calcareous sand loam	Climate chamber	Stephens et al. (1993)
A. t.	Geophagous	314	*Gaeumannomyces graminis*	43	Reduced disease severity[a]	Loam fine sandy	Greenhouse	Stephens et al. (1994)
A. t.	Geophagous	471	*Gaeumannomyces graminis*	68	Reduced disease severity[a]	Loam fine sandy	Greenhouse	Stephens et al. (1994)
A. t.	Geophagous	100	*Gaeumannomyces graminis*	33	Reduced disease severity[a]	Calcareous sandy loam	Field	Stephens et al. (1994)
A. r.	Geophagous	300	*Gaeumannomyces graminis*	28	Reduced disease severity[a]	Calcareous sandy loam	Field	Stephens et al. (1994)
A. t.	Geophagous	100	*Gaeumannomyces graminis*	39	Reduced disease severity[a]	Calcareous sandy loam	Field	Stephens et al. (1994)
A. t.	Geophagous	300	*Gaeumannomyces graminis*	36	Reduced disease severity[a]	Calcareous sandy loam	Field	Stephens et al. (1994)
A. t.	Geophagous	300	*Gaeumannomyces graminis*	28	Reduced disease severity[a]	Loam fine sandy	Field	Stephens et al. (1994)
L. t.	Detritivorous	118	*Fusarium culmorum*	99	Reduced *Fusarium* biomass[b]	12% clay, 85% silt, 3% sand	Climate chamber	Oldenburg et al. (2008)
L. t.	Detritivorous	177	*Fusarium culmorum*	98	Reduced *Fusarium* biomass[b]	12% clay, 85% silt, 3% sand	Field	Wolfarth et al. (2011)
L. t.	Detritivorous	313	*Oculimacula yallundae*	50	Reduction of necrosis severity[c]	29% clay, 55% silt, 17% sand	Greenhouse	Bertrand et al. (2015b)
L. t.	Detritivorous	313	*Oculimacula yallundae*	80	Reduction of necrosis severity[c]	29% clay, 55% silt, 17% sand	Greenhouse	Bertrand et al. (2015b)
A. c.	Geophagous	380	*Gaeumannomyces graminis*	68	Reduced infection rate	29% clay, 55% silt, 17% sand	Greenhouse	Puga-Freitas et al. (2016)
L. t.	Detritivorous	177	*Fusarium culmorum*	48–54	Reduced *Fusarium* biomass[b]	12% clay, 85% silt, 3% sand	Field	Meyer-Wolfarth et al. (2017)
L. t.	Detritivorous	177	*Fusarium culmorum*	88–92	Reduced *Fusarium* biomass[b]	14% clay, 80% silt, 6% sand	Field	Meyer-Wolfarth et al. (2017)

Earthworm species: *A.t.* = *Aporrectodea trapezoides*; *A. r.* = *Aporrectodea rosea*; *L. t.* = *Lumbricus terrestris*; *A. c.* = *Aporrectodea caliginosa*.

[a] The roots were rated for disease severity on a scale of 0–5, where 0 = no disease and 5 = maximum disease with 100% of primary roots severely truncated.

[b] Reduction of *Fusarium* biomass was analysed via ELISA methods and compared to the initial *Fusarium* biomass.

[c] Necrosis severity was scored with a four-class visual index, based on the proportion of the stem section destroyed by the fungus: 0 = no attack; 1 = less than 1/3 of the stem section destroyed, 2 = between 1/3 and 2/3 of the stem section destroyed, 3 = more than 2/3 of the stem section destroyed.

and the sustainability of soil management.

The reconciliation of both the external engineering agriculture and the internal ecosystem driven self-organizing mechanisms within common agricultural practices seems to be a key to create sustainable farming systems. The cultivation of agricultural land has well known negative and less known positive effects on biodiversity and related ES (Tscharntke et al., 2005; Tsiafouli et al., 2015). A loss in soil quality and functions will result in significant economic costs for users and society. However, farmers are via their choices of management practices in the position to counteract the negative effects of intensive farming.

3. Earthworms as ecosystem services mediators

Soil management practices can strongly affect earthworm communities and related processes depending on the intensity of the measures taken (Beylich et al., 2010; Holland, 2004). In general, earthworm abundance, biomass and species diversity is known to decrease significantly with higher intensity such as inversion tillage and pesticide use (Pelosi et al., 2014; van Capelle et al., 2012). There are reports of earthworm individual numbers (per m^2) from 30 (ploughing) to 400 (no-till) under field conditions (van Capelle et al., 2012; Rutgers et al. 2016; Frazao et al., 2017).

The impact earthworms have on soil processes and other soil organisms via their burrowing and mixing of soil and organic matter strongly depends on their functional traits (Brussaard et al., 2012), such as behavioral traits (deep burrowing, horizontal dwelling) and/or feeding traits (detritivorous, geophagous). The abundance of earthworms and the ratio of earthworm species representing these different types of traits were found to be of great importance for the provision of associated ES (Spurgeon et al., 2013). These interactions within and between soil biota communities are important drivers of self-regulation in soil and are fundamentally important for the control of harmful fungi. Suppression and degradation of plant pathogenic soil fungi by soil biota is an important ES, which together with other soil related ES has often been neglected from an agricultural viewpoint (Adhikari and Hartemink, 2016; Wall et al., 2015). In particular, bottom-up control by earthworms is considered to play an important role in biological control of soil-borne pathogens (Fig. 3). In the following, we are using the definition for pest and disease in conformity with EFSA (2017, p.35).

Besides a variety of ES provided by the soil ecosystem and its soil biota, there are also ecosystem disservices that may have harmful effects on human well-being (see e.g. Lubbers et al., 2013, pp. 187–194). For instance, there is evidence that earthworms can increase N_2O emissions from soils (Rizhiya et al., 2007; Lubbers et al., 2013). This disservice by earthworm activity depends on residue placement (on soil surface or incorporated) and earthworm functional group (Giannopoulos et al., 2010) as well as soil texture (Schorpp et al., 2016). Focusing on agricultural ecosystems, ecosystem disservices include the promotion of crop pests and pathogens which decrease productivity and can result even in complete crop loss (Zhang et al., 2007). Disservices are often associated with poor management of the agricultural system, for example the simplification of landscapes due to large-scale monocultures may cause pest outbreaks because natural enemies are negatively affected by habitat loss (Thies and Tscharntke, 1999; Weibull et al., 2003). Disservices may also occur under conservation tillage, when mulching techniques are used to protect soil from degradation. These techniques can significantly increase the risk of soil-borne plant pathogens infecting following crops (Pereyra and Dill-Macky, 2008). Pathogenic fungi such as *Fusarium* spp. may survive and colonise crop residues, which leads to an increased infection risk of the cultivated crops. Furthermore, toxigenic fungal plant pathogens are able to produce toxic secondary metabolites (mycotoxins).

Biological control and biodegradation options to reduce soil-borne plant pathogens and their environmental contaminants (such as mycotoxins) are coming into focus because soil processes supporting disease suppression being regarded as an ES (Fig. 3). In particular, the contribution of the deep burrowing earthworm species *Lumbricus terrestris* to biocontrol of fungal plant pathogens such as *Fusarium* species and their mycotoxins such as deoxynivalenol (DON) is highly relevant (Oldenburg et al., 2008; Wolfarth et al., 2011; Wolfarth et al., 2016; Meyer-Wolfarth et al., 2017).

Table 1 provides an overview of direct inhibitory effects of different earthworm species with two types of feeding traits (detritivorous, geophagous) on several fungal plant pathogens in wheat. Seven investigations have been evaluated taking into account the experimental conditions (climate chamber, greenhouse, field), the soil provided in the experiments and the individual density of earthworms (individuals m^{-2}). The summary in Table 1 revealed that the reduction effect of earthworms depends on the functional group and on the density of the earthworms. Detritivorous earthworm species reduced fungal infection or fungal inoculum by 48–99% with a mean reduction of 72%. Geophagous earthworm species reduced the disease parameters by an average of 43% (28–68%). Beside the degradation of fungal plant pathogens in wheat, earthworms also reduce the disease severity of major fungal pathogens (*Fusarium* spp., *Verticilium* spp.) infesting horticultural crops such as asparagus (50%), tomatoes (68%) and eggplant (28–61%) (Elmer, 2009; Elmer and Ferrandino, 2009).

In addition to direct inhibitory effects of earthworms on fungal plant pathogens, there are also reports of indirect impacts. It is for example well known that earthworms stimulate plant growth and plant production as reviewed by Van Groeningen et al. (2014). Table 2 summarises reports of plant growth effects of geophagous earthworm species on wheat when infected with the fungal plant pathogen *Gaeumannomyces graminis*. The listed reports demonstrate the potential of geophagous earthworms to affect plant growth parameter. The number of emerged plants increased by a mean of 20% in the presence of earthworms and in the case of the plant shoot weight an increase of 58% was measured. In one study even an increase (26%) of grain yield

Table 2
Indirect effects (increases in plant number, increased plant shoot weight, increased grain yield or increased plant height) of different geophagous earthworm species on the fungal plant pathogen *Gaeumannomyces graminis* in wheat considering the individual density of earthworms [Ind m^{-2}], the soil provided in the experiments and the experimental conditions (field, greenhouse) within an experimental time span of 9–10 weeks. The effects were measured compared to a non-earthworm control.

Earthworm species	[Ind m^{-2}]	Increase	Effect	Soil	Condition	Reference
A. t.	300	19%	Increased plant number	Loam fine sandy	Field	Stephens and Davoren (1995)
A. t.	300	67%	Increased plant shoot weight	Loam fine sandy	Field	Stephens and Davoren (1995)
A. r.	100	17%	Increased plant number	Loam fine sandy	Field	Stephens and Davoren (1995)
A. r.	300	24%	Increased plant number	Loam fine sandy	Field	Stephens and Davoren (1995)
A. r.	300	49%	Increased plant shoot weight	Loam fine sandy	Field	Stephens and Davoren (1995)
Mix of *A.t.*, *A. tub*, *A. c.*	70	26%	Increased grain yield	Orthic Brown Chernozemic loam	Field	Clapperton et al. (2001)
A. c.	380	39%	Increased plant height	29% clay, 55% silt, 16% sand	Greenhouse	Puga-Freitas et al. (2016)

Earthworm species: *A. t.* = *Aporrectodea trapezoides*; *A. r.* = *Aporrectodea rosea*; *A. tub.* = *Aporrectodea tuberculata*; *A. c.* = *Aporrectodea caliginosa*.

was reported (Clapperton et al., 2001). Tables 1 and 2 provide a set of cogent information for an economic valuation of an important ES of earthworms in agroecosystems and contribute to the answer of the question "What is the earthworm worth?" Furthermore, the presented data could complement the conceptual framework for economic valuation of such functional biodiversity coined by Pascual et al. (2015).

4. Ecosystem services in cropland – why this matters up to the grain world market

The dominance of wheat production in the EU has led to narrow cereal crop rotations that increase the risk of *Fusarium* infection, in particular when maize is grown before cereals, since maize residues are the most advantageous substrate for the colonisation and development of *Fusarium* fungi (Champeil et al., 2004; Leplat et al., 2013).

Severe outbreaks of *Fusarium* diseases can lead to (1) a significant yield loss up to 50% (Parry et al., 1995; Pasquali et al., 2016) and (2) quality reduction as a result of mycotoxin contamination of the grains (Leslie and Summerell, 2013). Due to their high toxicity, regulatory limits have been set by the European Commission (EC, 2006b, 2007), to protect humans from DON and other mycotoxin exposure through cereal grain consumption with a limit of 1.250 μg kg^{-1} in unprocessed cereals other than durum wheat, oats and maize (Regulation EC No. 1881/2006 and EC No. 1126/2007).

In most cereal production areas, current management to control this disease heavily relies on fungicides. Fungicide application directly before flowering is the most effective way to avoid early infection. However, the growing need for multiple fungicide applications has increased the economic cost for growers alongside with public concerns over pesticide risks and the evolution of pathogen resistance. This is particularly relevant because fungicide application never fully prevents that the cereals are colonised by *Fusarium*, in particular when humid weather conditions are facilitating the spreading of the disease. For instance, in a recent field trial in Lower Saxony (Germany), the mycotoxin levels could only be reduced by 50% and under favourable conditions up to 70% by applying an azole containing fungicide during cereal flowering (LK Niedersachsen, 2017).

Biocontrol methods represent an alternative to conventional management that can reduce pesticide risks and resistance development (Pertot et al., 2015). Based on the summarised evidence of Tables 1 and 2, we provide an example to demonstrate that earthworm activity is able to reduce the risk of *Fusarium*-related diseases and mycotoxin contamination. We are considering winter wheat production in the Lower Saxony region, Germany. In one scenario wheat is grown under conventional management practices, such as ploughing (Table 3) and in the other scenario under conservation tillage (without ploughing). Reduced soil disturbance in combination with thorough residue management fosters earthworm populations, reduces the possible inoculum source for *Fusarium*-related diseases and makes a reduced application of chemical fungicides possible. The calculation of the standard gross margin is a first step to calculate the economic value of the disease suppression effect of earthworms.

We have chosen standard gross margin (SGM) as a measure of the relative contribution of wheat production to overall farm revenue. For winter wheat a SGM is calculated per ha as separate activity to ensure comparability with other crops or farms in other regions of our research.

The calculation is based on regional datasets for Lower Saxony (Germany). For illustrative purposes we are assuming that the yield level is the same in all scenarios (taking the German average 2015–2017), ignoring other ES provided by earthworms than disease suppression. There are two different fungicide application regimes (Table 3): Two applications, which is the dominating practice in Lower Saxony (scenario A) and a reduced treatment with one application (B and C). In our German study region two fungicide applications occur on average during the vegetation period (information from the consulting service of the Chamber of Agriculture Lower Saxony and farmers' interviews). Reducing fungicide application under conventional wheat production, however, bears the risk of mycotoxin contamination, in particular under unfavourable humid weather conditions during flowering period. This leads to a situation where in some years the produced wheat can only be sold as lower quality wheat. Here we assume that wheat can only be sold at 149.03 EUR t^{-1} instead of 160.54 EUR t^{-1}, as it only reaches feed quality (AMI, 2019). In cases of higher mycotoxin contamination, the price may be even lower.

Depending on the type of cultivation the SGM in our example is 624 EUR ha^{-1} (scenario A: ploughing, 2 fungicide applications) or up to 699 EUR ha^{-1} (C: conservation tillage, 1 fungicide application). The SGM is increasing by 75 EUR ha^{-1} (+12%) because of well-active earthworm species. In a year with mycotoxin contamination under ploughing with reduced fungicide application (scenario B), the SGM is even 132 EUR ha^{-1} less than under scenario C. The disease suppression of earthworms goes along with additional long-term benefits, in particular improvements of the soil structure and the availability of nutrients. Therefore, it would be possible under scenario C to gradually further reduce inputs, in particular fertiliser application, reducing the risk of nutrient leaching and avoiding negative effects on water quality. The potential to recover functional and structural integrity after a disturbance, and to adapt to new circumstances, is generally defined as resilience. For the soil "this potential is a product of the past and the present soil management, and at the same time prospect of possible soil responses to future disturbances." (Ludwig et al., 2018). This stabilisation and improvement of resilience has an economic value that should also be added to the economic value calculated for the example in Table 3. However, due to limited data availability this part of additional economic benefits of ecosystem services in cropland cannot be included here and requires further research activities. While the example provided in Table 3 covers only wheat production it can be concluded that ES have a direct impact on productivity and profitability of crop production and consequently will improve the competitiveness of crop production on domestic and international markets.

As Robinson et al. (2014) concluded "value is much bigger than

Table 3
Standard gross margin (SGM) (€ ha^{-1}) for winter wheat in Lower Saxony (Germany) for different tillage systems and different fungicide applications (for details see the Supplementary data).
Sources: Own calculations based on data from: LWK NDS (2019), LWK NRW (2018), Agravis (2018), KTBL (2018), Landesamt für Statistik Niedersachsen (2018).

	A: Wheat under conventional tillage with 2 fungicide applications (€ ha^{-1})	B: Wheat under conventional tillage with 1 fungicide application (€ ha^{-1})	C: Wheat under conservation tillage with 1 fungicide application (€ ha^{-1})
Sale price (8.56 t ha^{-1})	1374	1276	1374
Seed, fertiliser, hail insurance and plant protection except fungicides	443	443	443
Fungicides	82	41	41
Machinery costs	225	225	191
Sum costs	750	709	675
Standard gross margin (SGM)	**624**	**567**	**699**

simply monetary value" and with this comparison of production costs lowering due to healthy and active soil biota like the earthworms there is the extrinsic value that is recognisable and simple to demonstrate.

5. Discussion and Implications

In this paper we demonstrate that soil organisms and in particular earthworms support a wide range of soil-associated ES which can stabilise yields and ensure good quality products, while at the same time improving the resilience of crops that are under water or other climatic stresses. Demonstrating the positive effect on the standard gross margin is only a first step to quantify positive effects deriving from healthy soils with abundant soil life at farm level and finally for the society.

An economic assessment of earthworm services would foster and encourage farmers to implement practices that contribute to enhanced soil quality, disease prevention and the sustainability of soil management. Soil management, however, plays the key role in the design of sustainable cropping systems (Roger-Estrade et al., 2010). Organic residue management, prevention of compaction, crop rotation and the timing of cultivation, must be considered together, with an assessment of their impact on pests and their natural enemies and on ecosystem engineers (Roger-Estrade et al., 2010). Farmers benefit from the biocontrol service provided by earthworms as listed in Tables 1 and 2. The provision of ES by earthworm species directly contributes to a significant reduction of disease prevalence which in economic terms reduces the need for pesticide application and hence, leads to a reduction in production cost with a positive effect on the economy of crop production. The control of fungal pathogens like *Fusarium* species and their mycotoxins can be managed by farmers in interaction with the soil-inhabiting organisms in agroecosystems. Combating measures of farmers and the degrading activities of soil fauna may result in synergistic effects to control pathogenic fungi as well as their mycotoxins to stabilise yields and improve (or at least maintain) the quality and quantity of crop products and crop residues. Through the combination of good agricultural practice (residue management, sustainable crop rotation, less susceptible cultivars and sustainable fungicide application) by farmers (Busch et al., 2015) and the provision of ecosystem services by soil fauna an effective control of pathogens and pollutants can be achieved. The natural mechanism of self-regulation in the soil system is promoted by farmer's residue management.

Research is needed that involves stakeholders in order to obtain more knowledge of farm management tools influencing the soil biota, and design innovations at the crop and farming system levels. As stated by Mills et al. (2017) "At the societal level changing farmers' values and beliefs is easier if they recognise that it is something that society wants and values". As shown in our conceptual framework (Fig. 2) the farmer is at the interface between two systems: On the one hand using modern technologies to dominate nature and control production risks from natural constraints but ultimately still depending on natural regulation processes and their biotic actors as companions in an agricultural-ecological production system.

Under the current global market based system a first step towards sustainable farming is a combination of smart farming and promotion/growth of sustainable farming. Smart farming is under way to use information and communication technology in the cyber-physical farm management cycle (Wolfert et al., 2017) to increase sustainable intensification of global agriculture. New technologies such as weed robots, better analysis technologies, genetically modified organism and the widespread use of data combines the farm based production approach with the systems approach. The nutrient status of the system that is worked in is taken into account and management input is adjusted to what is actually needed rather than overusing already scarce resources.

The hidden costs of resource depletion that are not part of the private costs create negative externalities in agricultural production. However, on the other hand, farmers provide positive externalities, which are not paid in the markets. Thus, policy measures are required to bridge the gap between private and social costs or benefits of sustainable soil management.

6. Outlook

This paper uses an analysis of earthworm fungal interactions to exemplify to what extent soil organisms can contribute to the well-being and welfare of farmers, consumers and people. To enhance yield they are substituted on-farm by the technologies and innovations of the "green revolution". The current research agenda with its own trend of specialization and intensification in each discipline seems to produce too many insights into details which are basically not enhancing or substituting technologies in farming by ES nor do they have an immediate impact on the profits of farmers. Although, there is a need for policy action in the form of new subsidies or regulations, even more needed is a closer cooperation and understanding between different scientific disciplines, in particular soil researchers and economists in order to support land users on their way towards a more sustainable farm management with concrete and profitable alternatives to the current technological mix used. The reconciliation of the external engineering agriculture linked to the global economic circulation and the internal ecosystem driven self-organizing mechanisms that can be managed by common agricultural practices is taken as a key to define an economic value for soil biota mediating ecosystem services.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2019.02.003.

Acknowledgements

The SoilMan project (grant number 01LC1620) was funded through the 2015–2016 BiodivERsA COFUND call for research proposals, with the national funders Federal Ministry of Education and Research (BMBF), The French National Research Agency (ANR), The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS), Ministry of Economy and Competitiveness (MINECO), Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI) and Estonian Research Council (ETAG). We also thank Dr. Joachim Weinert (Agricultural Chamber of Lower Saxony) for his valuable scientific advice concerning diseases management and fungicide application strategies in Lower Saxony, Germany.

References

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services – a global review. Geoderma 262, 101–111. https://doi.org/10.1016/j.geoderma.2015.08.009.
Agravis, 2018. Agravis Cloppenburg (Niedersachsen), Verrechnungspreisliste 2018.
AMI, 2019. Agrarmarkt Informations-Gesellschaft mbH. https://www.ami-informiert.de/ami-maerkte, Accessed date: January 2019.
Barrios, E., 2007. Soil biota, ecosystem services and land productivity. Ecol. Econ. 64, 269–285.
Bengtsson, J., 2010. Applied (meta)community ecology: diversity and ecosystem services at the intersection of local and regional processes. Chapter 9. In: Verhoef, H.A., Morin, P.J. (Eds.), Community Ecology. Oxford University Press, pp. 115–130.
Bengtsson, J., 2015. Biological control as an ecosystem service: partitioning contributions of nature and human inputs to yield. Ecol. Entomol. 40 (Suppl. 1), 45–55. https://doi.org/10.1111/een.12247.
Bengtsson, J., Jones, H., Setälä, H., 1997. The value of biodiversity. Trends Ecol. Evol. 12, 334–336.
Bertrand, M., Barot, S., Blouin, M., Whalen, J., de Oliveira, T., Roger-Estrade, J., 2015a. Earthworm services for cropping systems. A review. Agron. Sustain. Dev. 35, 553–567.
Bertrand, M., Blouin, M., Barot, S., Charlier, A., Marchand, D., Roger-Estrade, J., 2015b. Biocontrol of eyespot disease on two winter wheat cultivars by an anecic earthworm (Lumbricus terrestris). Appl. Soil Ecol. 96, 33–41.
Beylich, A., Oberholzer, H.-R., Schrader, S., Höper, H., Wilke, B.-M., 2010. Evaluation of soil compaction effects on soil biota and soil biological processes in soils. Soil Tillage Res. 109, 133–143.
Brussaard, L., Aanen, D.K., Briones, M.J.I., Decaëns, T., De Deyn, G.B., Fayle, T.M., James, S.W., Nobre, T., 2012. Biogeography and phylogenetic community structure of soil invertebrate ecosystem engineers: global to local patterns, implications for ecosystem

functioning and services and global environmental change impacts. In: Wall, D.H. (Ed.), Soil Ecology and Ecosystem Services. Oxford University Press, Oxford, pp. 201–232.
Busch, M., Brandhuber, R., Breitschuh, T., Brunotte, J., Bug, J., Chappuis, A., von Fröba, N., Henke, W., Honecker, H., Höppner, F., List, M., Mosimann, T., Ortmeier, B., Schmidt, W., Schrader, S., Vorderbrügge, T., Weyer, T., 2015. Gute fachliche Praxis - Bodenbewirtschaftung und Bodenschutz, 2. Aufl. AID, Bonn.
Champeil, A., Fourbet, J.F., Doré, T., Rossignol, L., 2004. Influence of cropping system on Fusarium head blight and mycotoxin levels in winter wheat. Crop Prod. 23, 531–537.
Clapperton, M.J., Lee, N.O., Binet, F., Conner, R.L., 2001. Earthworms indirectly reduce the effects of take all (Gaeumannomyces graminis var. tritici) on soft white spring wheat (Triticum aestivum cv. Filder). Soil Biol. Biochem. 33, 1531–1538.
Clements, R.O., Murray, P.J., Sturdy, R.G., 1991. The impact of 20 years of absence of earthworms and three levels of N fertilizer on a grassland soil environment. Agric. Ecosyst. Environ. 36, 75–85.
Collaku, A., Harrison, S.A., 2002. Losses in wheat due to waterlogging. Crop Sci. 42, 444–450. https://doi.org/10.2135/cropsci2002.4440.
Costanza, R., dArge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Costanza, R., deGroot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008.
Daily, G.C. (Ed.), 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, Washington DC.
Decaëns, T., Jiménez, J.J., Gioia, C., Measey, G.J., Lavelle, P., 2006. The values of soil animals for conservation biology. Eur. J. Soil Biol. 42, 23–38.
EFSA, 2017. Scientific opinion addressing the state of the science on risk assessment of plant protection products for in-soil organisms. EFSA J. 15 (2), 4690. https://efsa.onlinelibrary.wiley.com/doi/epdf/10.2903/j.efsa.2017.4690, Accessed date: January 2019.
Elmer, W.H., 2009. Influence of earthworm activity on soil microbes and soilborne diseases of vegetables. Plant Dis. 93, 175–179.
Elmer, W.H., Ferrandino, F.J., 2009. Suppression of verticillium wilt of eggplant by earthworms. Plant Diseases 93, 485–489.
ELN-FAB, 2012. Functional Agrobiodiversity: Nature Serving Europe's Farmers. ECNC-European Centre for Nature Conservation, Tilburg, Niederlande. http://ec.europa.eu/environment/nature/natura2000/platform/documents/functional_agrobiodiversity_eln-fab_publication_en.pdf, Accessed date: January 2019.
European Commission, 2006a. Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC. COM(2006) 232 final. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0232:FIN:EN:PDF, Accessed date: January 2019.
European Commission, 2006b. Commission regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs. Off. J. Eur. Union L 364, 5–24 (20.12.2006).
European Commission, 2007. Commission regulation (EC) No 1126/2007 of 28 September 2007 amending regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs as regards Fusarium toxins in maize and maize products. Off. J. Eur. Union L 255, 14–17 (29.9.2007).
Eurostat, 2017. Main annual crop statistics. http://ec.europa.eu/eurostat/statistics-explained/index.php/Main_annual_crop_statistics#Cereals, Accessed date: January 2019.
Faber, J.H., Noordijk, J., Scheper, J.A., 2016. Functionele agrobiodiversiteit. In: de Snoo, G.R., Melman, Th.C.P., Brouwer, F.M., van der Weijden, W.J., de Haes, H.A.U. (Eds.), Agrarisch natuurbeheer in Nederland – Principes, resultaten en perspectieven. Wageningen Academic Publishers, pp. 251–272.
FAO, ITPS, 2015. Status of the World's Soil Resources – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.
Frazao, J., de Goede, R.G.M., Brussaard, L., Faber, J.H., Groot, J.C.J., Pulleman, M.M., 2017. Earthworm communities in arable fields and restored field margins, as related to management practices and surrounding landscape diversity. Agric. Ecosyst. Environ. 248, 1–8. https://doi.org/10.1016/j.agee.2017.07.014.
Geiger, F., Bengtsson, J., Berendse, F., Weisser, W.W., Emmerson, M., Morales, M.B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L.W., Dennis, C., Palmer, C., Oñate, J.J., Guerrero, I., Hawro, V., Aavik, T., Thies, C., Flohre, A., Hänke, S., Fischer, C., Goedhart, P.W., Inchausti, P., 2010. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl. Ecol. 11, 97–105.
Giannopoulos, G., Pulleman, M.M., van Groenigen, J.W., 2010. Interactions between residue placement and earthworm ecological strategy affect aggregate turnover and N_2O dynamics in agricultural soil. Soil Biol. Biochem. 42, 618–625.
Glaesner, N., Helming, K., de Vries, W., 2014. Do current European policies prevent soil threats and support soil functions? Sustainability 6, 9538–9563. https://doi.org/10.3390/su6129538.
Gómez-Baggethun, E., de Groot, R., Lomas, P.L., Montes, C., 2010. The history of ecosystem services in economic theory and practice: From early notions to markets and payment schemes. Ecol. Econ. 69, 1209–1218.
Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ. 103, 1–25.
Jones, C.G., Lawton, J.H., Shachak, M., 1994. Organisms as ecosystem engineers. Oikos 69, 373–386.
Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerda, A., Montanarella, L., Quinton, J.N., Pachepsky, Y., van der Putten, W.H.B., Bardgett, R.D., Moolenaar, S., Mol, G., Jansen, B., Fresco, L.O., 2016. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. Soil 2, 111–128. https://doi.org/10.5194/soil-2-111-2016.
KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft), 2018. Faustzahlen für die Landwirtschaft, 15. Auflage. 978-3-945088-59-3.
Landesamt für Statistik Niedersachsen, 2018. Statistische Berichte Niedersachsen, Bodennutzung und Ernte 2017. https://www.statistik.niedersachsen.de/themenbereiche/landwirtschaft/ernte/erntestatistik-online—aktuelle-ernteberichte-niedersachsen-152835.html, Accessed date: January 2019.
Lavelle, P., Bignell, D., Lepage, M., 1997. Soil function in a changing world: the role of invertebrate ecosystem engineers. Eur. J. Soil Biol. 33, 159–193.
Leplat, J., Friberg, H., Abid, M., Steinberg, C., 2013. Survival of Fusarium graminearum, the causal agent of Fusarium head blight. A review. Agron. Sustain. Dev. 33, 97–111. https://doi.org/10.1007/s13593-012-0098-5.
Leslie, J.F., Summerell, B.A., 2013. An overview of Fusarium. In: Brown, D.W., Proctor, R.H. (Eds.), Fusarium: Genomics, Molecular and Cellular Biology. Caister Academic Press, USA, pp. 1–10.
LK (Landwirtschaftskammer) Niedersachsen, 2017. Gelbrost auch 2017 wichtigste Krankheit im Winterweizen? Ergebnisse der Landessortenversuche 2017. Heft 10, Weizen 2017. https://docplayer.org/76762060-Gelbrost-auch-2017-wichtigste-krankheit-im-winterweizen.html, Accessed date: January 2019.
Lubbers, I.M., van Groenigen, K.J., Fonte, S.J., Six, J., Brussaard, L., van Groenigen, J.W., 2013. Greenhouse-gas emissions from soils increased by earthworms. Nat. Clim. Chang. 3, 187–194.
Ludwig, M., Wilmes, P., Schrader, S., 2018. Measuring soil sustainability via soil resilience. Sci. Total Environ. 626, 1484–1493. https://doi.org/10.1016/j.scitotenv.2017.10.043.
LWK NDS, 2019. Beispiele zur Bekämpfung von Pilzkrankheiten im Winterweizen 2018. https://www.lwk-niedersachsen.de/index.cfm/portal/pflanze/nav/504/article/32208.html, Accessed date: 1 January 2019.
LWK Nordrhein-Westfalen, 2018. Ratgeber Pflanzenbau und Pflanzenschutz Ausgabe 2018.
MA, Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well Being: Synthesis. Island Press, Washington DC.
Meyer-Wolfarth, F., 2016. Biological Control of Plant Pathogenic Fungi and the Regulation of Mycotoxins by Soil Fauna Communities in a Conservation Tillage System as Ecosystem Services for Soil Health. Trier University. http://ubt.opus.hbz-nrw.de/volltexte/2017/1022/pdf/Diss_Meyer_Wolfarth_genehmigt.pdf, Accessed date: January 2019 (PhD Thesis).
Meyer-Wolfarth, F., Schrader, S., Oldenburg, E., Weinert, J., Brunotte, J., 2017. Repression of the toxigenic fungi Fusarium culmorum by soil fauna in an agroecosystem. Mycotoxin Res. 33, 237–244.
Mills, J., Gaskell, P., Ingram, J., Dwyer, J., Reed, M., Short, C., 2017. Engaging farmers in environmental management through a better understanding of behaviour. Agric. Hum. Values 34, 283–299. https://doi.org/10.1007/s10460-016-9705-4.
Oldenburg, E., Kramer, S., Schrader, S., Weinert, J., 2008. Impact of the earthworm Lumbricus terrestris on the degradation of Fusarium-infected and deoxynivalenol-contaminated wheat straw. Soil Biol. Biochem. 40, 3049–3053.
Palomo, I., Felipe-Lucía, M.R., Bennet, E.M., Martín-López, B., Pascual, U., 2016. Disentangling the pathways and effects of ecosystem service co-production. Adv. Ecol. Res. 54, 245–283. https://doi.org/10.1016/bs.aecr.2015.09.003.
Parry, D.W., Jenkinson, P., McLeod, L., 1995. Fusarium ear blight (scab) in small grain cereals - a review. Plant Pathol. 44, 207–238.
Pascual, U., Termansen, M., Hedlund, K., Brussaard, L., Faber, J., Foudi, S., Lemanceau, P., Liv-Jørgensen, S., 2015. On the value of soil biodiversity and ecosystem services. Ecosyst. Serv. 15, 11–18. https://doi.org/10.1016/j.ecolser.2015.06.002.
Pasquali, M., Beyer, M., Logrieco, A., Audenaert, K., Balmas, V., Basler, R., Boutigny, A.-L., Chrpová, J., Czembor, E., Gagkaeva, T., González-Jaén, M.T., Hofgaard, I.S., Köycü, N.D., Hoffmann, L., Lević, J., Marin, P., Miedaner, T., Migheli, Q., Moretti, A., Müller, M.E.H., Munaut, F., Parikka, P., Pallez-Barthel, M., Piec, J., Scauflaire, J., Scherm, B., Stankovic, S., Thrane, U., Uhlig, S., Vanheule, A., Yli-Mattila, T., Vogelgsang, S., et al., 2016. A European database of *Fusarium graminearum* an F. culmorum trichothecene genotype. Front. Microbiol. 7, 406.
Pelosi, C., Barot, S., Capowiez, Y., Hedde, M., Vandenbulcke, F., 2014. Pesticides and earthworms. A review. Agron. Sustain. Dev. 34, 199–228. https://doi.org/10.1007/s13593-013-0151-z.
Pereyra, S.A., Dill-Macky, R., 2008. Colonization of the residues of diverse plant species by Gibberella zeae and their contribution to Fusarium head blight inoculum. Plant Dis. 92, 800–807.
Pertot, I., Alabouvette, C., Hinarejos, E., Franca, S., 2015. Mini paper—the use of microbial biocontrol agents against soil-borne diseases. EIP-AGRI Focus Group Soil-borne diseases. https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/8_eip_sbd_mp_biocontrol_final.pdf, Accessed date: January 2019.
Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. B Biol. Sci. 365, 2959–2971.
Puga-Freitas, R., Belkacem, L., Barot, S., Bertrand, M., Roger-Estrade, J., Blouin, M., 2016. Transcriptional profiling of wheat in response to take-all disease and mechanism involved in earhtworm's biocontrol effect. Eur. J. Plant Pathol. 144, 155–165.
Rist, L., Felton, A., Nyström, M., Troell, M., Sponseller, R.A., Bengtsson, J., Österblom, H., Lindborg, R., Tidåker, P., Angeler, D.G., Milestad, R., Moen, J., 2014. Applying resilience thinking to production ecosystems. Ecosphere 5 (6), 73. https://doi.org/10.1890/ES13-00330.1.
Rizhiya, E., Bertora, C., van Vliet, P.C.J., Kuikman, P.J., Faber, J.H., van Groenigen, J.W., 2007. Earthworm activity as a determinant for N_2O emission from crop residue. Soil Biol. Biochem. 39, 2058–2069.

Robinson, D.A., Fraser, I., Dominati, E.J., Davíðsdóttir, B., Jónsson, J.O.G., Jones, L., Jones, S.B., Tuller, M., Lebron, I., Bristow, K.L., Souza, D.M., Banwart, S., Clothier, B.E., 2014. On the value of soil resources in the context of natural capital and ecosystem service delivery. Soil Sci. Soc. Am. J. 78 (3), 685–700. https://doi.org/10.2136/sssaj2014.01.0017.
Roger-Estrade, J., Anger, C., Bertrand, M., Richard, G., 2010. Tillage and soil ecology: partners for sustainable agriculture. Soil Tillage Res. 111, 33–40.
Rutgers, M., Orgiazzi, A., Gardi, C., Römbke, J., Jänsch, S., Keith, A.M., Neilson, R., Boag, B., Schmidt, O., Murchie, A.K., Blackshaw, R.P., Pérès, G., Cluzeau, D., Guernion, M., Briones, M.J.I., Rodeiro, J., Piñeiro, R., Díaz Cosín, D.J., Sousa, J.P., Suhadolc, M., Kos, I., Krogh, P.-H., Faber, J.H., Mulder, C., Bogte, J.J., van Wijnen, H.J., Schouten, A.J., de Zwart, D., 2016. Mapping earthworm communities in Europe. Appl. Soil Ecol. 97, 98–111. https://doi.org/10.1016/j.apsoil.2015.08.015.
Schorpp, Q., Riggers, C., Lewicka-Szczebak, D., Giesemann, A., Well, R., Schrader, S., 2016. Influence of Lumbricus terrestris and Folsomia candida on N_2O formation pathways in two different soils – with particular focus on N_2 emissions. Rapid Commun. Mass Spectrom. 30, 2301–2314. https://doi.org/10.1002/rcm.7716.
Spurgeon, D.J., Keith, A.M., Schmidt, O., Lammertsma, D.R., Faber, J.H., 2013. Land-use and land-management change: relationships with earthworm and fungi communities and soil structural properties. BMC Ecol. 13, 46.
Stephens, P.M., Davoren, C.W., 1995. Effect of the lumbricid earthworm Aporrectodea trapezoids on wheat grain yield in the field, in the presence or absence of Rhizoctonia solani and Gaeumannomyces graminis var. tritici. Soil Biol. Biochem. 28 (4/5), 561–567.
Stephens, P.M., Davoren, C.W., Doube, B.M., Ryder, M.H., Benger, A.M., Neate, S.M., 1993. Reduced severity of Rhizoctonia solani disease on wheat seedlings associated with the presence of the earthworm Aporrectodea trapezoids (Lumbricidae). Soil Biol. Biochem. 25 (11), 1477–1484.
Stephens, P.M., Davoren, C.W., Doube, B.M., Ryder, M.H., Benger, A.M., Neate, S.M., 1994. Ability of the lumbricid earthworms Aporrectodea rosea and Aporrectodea trapezoids to reduce the severity of take-all under greenhouse and field conditions. Soil Biol. Biochem. 26 (10), 1291–1297.
Tancoigne, E., Barbier, M., Cointet, J.P., Richard, G., 2015. The place of agricultural sciences in the literature on ecosystem services. Ecosyst. Serv. 10, 35–48. https://doi.org/10.1016/j.ecoser.2014.07.004.
Thies, C., Tscharntke, T., 1999. Landscape structure and biological control in agroecosystems. Science 285, 893–895.
Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecol. Lett. 8 (8), 857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x.
Tsiafouli, M.A., Thébault, E., Sgardelis, S.P., de Ruiter, P.C., van der Putten, W.H., Birkhofer, K., Hemerik, L., de Vries, F., Bardgett, R.D., Brady, M.V., Bjornlund, L., Bracht Jorgensen, H., Christensen, S., D'Hertfeldt, T., Hotes, S., Gera Hol, W.H., Frouz, J., Mortimer, S.R., Setala, H., Tzanopoulos, J., Uteseny, K., Oizl, V., Stary, J., Wolters, V., Hedlund, K., 2015. Intensive agriculture reduces soil biodiversity across Europe. Glob. Chang. Biol. 21, 973–985.
Turbé, A., De Toni, A., Benito, P., Lavelle, P., Lavelle, P., Ruiz, N., Van der Putten, W.H., Labouze, E., Mudgal, S., 2010. Soil biodiversity: functions, threats and tools for policy makers. Bio Intelligence Service, IRD, and NIOO, report for European Commission (DG Environment). http://ec.europa.eu/environment/archives/soil/pdf/biodiversity_report.pdf, Accessed date: January 2019.
UK NEA (UK National Ecosystem Assessment), 2011. The UK National Ecosystem Assessment: Synthesis of the Key Findings. UNEP-WCMC, Cambridge.
UN (United Nations), 2015. The Millennium Development Goals Report 2015. United Nationshttp://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf, Accessed date: January 2019.
UN General Assembly, 2015. Transforming our world: the 2030 Agenda for Sustainable Development, 21 October 2015, A/RES/70/1. http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E, Accessed date: January 2019.
van Capelle, C., Schrader, S., Brunotte, J., 2012. Tillage-induced changes in the functional diversity of soil biota – a review with a focus on German data. Eur. J. Soil Biol. 50, 165–181.
Van Doorn, A., Westerink, J., Nieuwenhuizen, W., Melman, D., Schrijver, R., Breman, B., 2017. Verder vergroenen, verder verbreden; Naar een effectieve bijdrage van het Europees landbouwbeleid en het beleid voor agrarisch natuurbeheer aan groene opgaven. Wageningen Environmental Research, Wageningen Environmental Research, Wageningen (Rapport 2822).
Van Groeningen, J.W., Lubbers, I.M., Vos, H.M.J., Brown, G.G., De Deyn, G.B., van Groeningen, K.J., 2014. Earthworms increase plant production: a meta-analysis. Sci. Rep. 4, 6365.
Wall, D.H. (Ed.), 2012. Soil Ecology and Ecosystem Services. Oxford University Press.
Wall, D.H., Nielsen, U.N., Six, J., 2015. Soil biodiversity and human health. Nature 528, 69–76. https://doi.org/10.1038/nature15744.
Weibull, AC., Östman, Ö., Granqvist, Å, 2003. Biodivers. Conserv. 12. pp. 1335. https://doi.org/10.1023/A:1023617117780.
Wolfarth, F., Schrader, S., Oldenburg, E., Weinert, J., Brunotte, J., 2011. Earthworms promote the degradation of Fusarium biomass and deoxinivalenol content in wheat straw under field conditions. Soil Biol. Biochem. 43, 1858–1865.
Wolfarth, F., Schrader, S., Oldenburg, E., Brunotte, J., 2016. Mycotoxin contamination and its regulation by the earthworm species Lumbricus terrestris in presence of other soil fauna in an agroecosystem. Plant Soil 402, 331–342.
Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M.-J., 2017. Big data in smart farming – a review. Agric. Syst. 153, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023.
Zhang, W., Ricketts, T.H., Kremen, C., Carney, K., Swinton, S.M., 2007. Ecosystem services and dis-services to agriculture. Ecol. Econ. 64, 253–260.