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BonaRes Series 2020/5 | DOI: 10.20387/BonaRes-BSZH-QBKN

Ittner, S., Gerdes, H., Athmann, M.,
Bauke, S., Gocke, M., Guigue, J., Jaiswal, S.,
Kautz, T., Schmittmann, O., Schulz, S., Seidel, S.

The impact of subsoil management on the delivery of ecosystem services

Soil as a Sustainable Resource for the Bioeconomy - BonaRes is a research programme funded by the German Ministry of Education and Research (BMBF).

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Imprint

Editor: BonaRes Centre for Soil Research
c/o Helmholtz Centre for Environmental Research - UFZ
Department of Soil System Science
Theodor-Lieser-Str. 4 | 06120 Halle (Saale), Germany
Phone: (+49) 345 558 5226 | E-Mail: info@bonares.de
www.bonares.de

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Authors

Ittner, Sophie – Ecologic Institut, Berlin
Gerdes, Holger – Ecologic Institut, Berlin
Athmann, Miriam – Universität Bonn
Bauke, Sara – Universität Bonn
Gocke, Martina – Universität Bonn
Guigue, Julien – Technische Universität München
Jaiswal, Sanjay – Technische Universität München
Kautz, Timo – Humboldt-Universität zu Berlin
Schmittmann, Oliver – Universität Bonn
Schulz, Stefanie – Helmholtz Zentrum München
Seidel, Sabine – Universität Bonn

Correspondence sophie.ittner@ecologic.eu

Date October 2020

Abstract

In recent years, the interest in subsoil has increased, since it can hold immense reservoirs of nutrients, organic matter and water. The subsoil can therefore provide important ecosystem services for the agricultural production system and beyond. This paper assesses the sustainability of two subsoil management measures with regard to the delivery of soil-related ecosystem services: a) the cultivation of deep-rooted pre-crops (biological approach) and b) stripwise mechanical subsoil loosening in combination with the incorporation of compost (*Soil³ method*). The analysis includes the identification of soil-related ecosystem services to which the subsoil contributes, the identification of related indicators, and the analysis of changes in the delivery of ecosystem services. The results show that both subsoil management measures lead to a change in the provision of soil-related ecosystem services. With the exception of the effect on potential N-leaching, both measures have an overall positive effect on considered ecosystem services.

Keywords BonaRes, subsoil, ecosystem services, bioeconomy, Soil³

Acknowledgement

This work was funded by the German Federal Ministry of Education and Research (BMBF) in the framework of the funding measure “Soil as a Sustainable Resource for the Bioeconomy – BonaRes”, project “Soil³ - Sustainable Subsoil Management, subproject 6” (Grant 031B0515F).

The impact of subsoil management on the delivery of ecosystem services

Sophie Ittner and Holger Gerdes

in collaboration with Miriam Athmann, Sara Bauke, Martina Gocke, Julien Guigue, Sanjay Jaiswal, Timo Kautz, Oliver Schmittmann, Stefanie Schulz and Sabine Seidel

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1 Introduction

1.1 Subsoil management

The term 'subsoil' describes the soil layers beneath the tilled or formerly tilled soil in arable farming systems, i.e. approx. 30 cm beneath the surface. In contrast to the topsoil, the subsoil is generally characterized by high bulk density, low air permeability and a low concentration of organic matter. The latter is linked to the overall lower nutrient content and number of microbes compared to the topsoil. This is one of the reasons why farmers pay little attention to the subsoil.

In recent years, the interest in subsoil has increased, since it can hold immense reservoirs of nutrients, organic matter and water (Gaiser et al., 2012; Kautz et al., 2013; Lynch & Wojciechowski, 2015; Schneider & Don, 2019a; Schneider & Don, 2019b). Research has shown that the subsoil is able to provide nutrition for crops and to sustain yields, especially under poor growing conditions, such as depleted topsoil and droughts (Gaiser et al., 2012; Kautz et al., 2013; Lynch & Wojciechowski, 2015). More specifically, the contribution of subsoils to plant nutrition may vary from less than 10% to more than 70% for certain nutrients (Kautz et al., 2013). However, high penetration resistance due to high bulk density and compacted soil layers prevent root growth into deeper soil layers, so that these resources often remain inaccessible for plants (Schneider & Don, 2019a). In Germany, 71% of all agricultural soils show potential rooting to less than 100 cm depth in particular due to compactness (Schneider & Don, 2019a).

There are various mechanical and biological methods to overcome such compacted soil layers and facilitate root growth into deeper layers. "Subsoiling", i.e. loosening of deep soil layers with special tillage machinery is one option often used to combat subsoil compaction, which can cause substantial yield decreases (Evans et al., 1996; Leskiw et al., 2012; Schjønning et al., 2015). Loosening the subsoil is supposed to increase crop yields especially in dry years by enabling deeper and wider root growth, improving water infiltration and transport and facilitating nutrient uptake (Cai et al., 2014). However, the effects of mechanical subsoil loosening are controversially discussed (Kautz et al., 2013; Schjønning et al., 2015). In particular, it is often criticized that subsoiling has a detrimental effect on soil structure and leads to less resilience and recompaction after mechanical loosening (Leskiw et al., 2012; Munkholm et al., 2005; Schjønning et al., 2015). Evans et al. (1996) concluded that one-time subsoil tillage has no long-term beneficial effect on grain yields and is not economically efficient. In addition, as the technique requires a considerable input of energy, it incurs high costs to the farmer (Kautz et al., 2013). Based on the German agricultural soil inventory, Schneider & Don (2019b) showed that deep soil tillage is not very popular among farmers and takes place on only 5% of German agricultural land with root restricted soil layers.

Another opportunity for roots to overcome a layer of compacted soil is the use of large-sized biopores formed by roots and earthworms as preferential growth pathways (Landl et al., 2019; Kautz, Athmann & Köpke, 2014). Biopores are hotspots with particularly high organic matter, microbial activity and nutrient availability (Kautz, Athmann & Köpke, 2014; Kuzyakov & Blagodatskaya, 2015), they enhance water infiltration and have a proven beneficial impact on root water uptake in times of drought (Landl et al., 2019; Gaiser et al., 2012). Biopores can remain in the subsoil over years. Thus, a softer and less cost-intensive biological approach is the use of deep-rooting pre- or intercrops, which are able to penetrate compacted subsoil layers (Gaiser et al., 2012; Gill et al., 2008; Yunusa & Newton, 2003). Examples of suitable primer crops with mechanically resilient root systems include lucerne, chicory and lupine.

An innovative subsoil management technique that potentially bypasses the disadvantages of subsoiling is complementing mechanical subsoil loosening with incorporating organic material (e.g. green clippings, compost) into the subsoil. It is assumed that this technique increases the subsoil's resistance to deformation and its elasticity, thereby reducing the risk of (re-)compaction in the long term. Few experiments have tested the technique. These studies show that the incorporation of organic material may lead to higher root density, increased availability of nutrients and thus increased nitrogen supply and uptake, and may contribute to higher crop yields compared to the compacted control field (Adcock et al. 2007; Leskiw et al., 2012; Gill et al., 2008). In addition, the technique may enhance the subsoil's ability to store water (Leskiw et al., 2012; Zhang et al., 2005) and improve water uptake from the subsoil (Gill et al. 2008).

1.2 Scope of the analysis

This paper assesses the sustainability of two subsoil management measures: a) the cultivation of deep-rooted pre-crops (biological approach) and b) stripwise mechanical subsoil loosening in combination with the incorporation of compost (*Soil³ method*). These methods explored by the Soil³ project have the potential to stimulate root growth into deeper soil layers and thus make the resources available to the plants in the subsoil, reduce subsoil compaction and thereby minimize or prevent the risk of recompaction. In order to classify subsoil management measures as sustainable, measures have to be cost-efficient at societal level (macro-economic assessment) and cost-effective at farm level (micro-economic assessment). Based on scientific studies and data collected within the Soil³ project, this paper summarizes the environmental effects caused by subsoil management measures to assess the impact on a societal level.

For this purpose, a comprehensive concept, which considers soil functions as a whole, is required. The ecosystem services (ESS) concept is particularly well suited for this purpose and is used to assess environmental impacts of subsoil management measures. ESS are defined as "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005), including provisioning services, regulation and maintenance services and cultural services (CICES classification). The analysis includes a) the identification of soil-related ESS to which the subsoil contributes, b) the identification of related indicators, and c) the analysis of changes in the provision of ESS. Societal costs and benefits of subsoil management are determined by assessing whether subsoil management measures lead to an increased or decreased provision of soil-related ESS. Based on actual measurements of specific indicators, a cost-benefit analysis of alternative subsoil management measures will be conducted in a later phase of the Soil³ project.

2 Methods

2.1 Linking subsoil to the delivery of ecosystem services – expert survey

The relevance of the subsoil for the delivery of soil-related ESS is largely unexplored. In order to overcome the apparent knowledge gap, an online survey was developed in Phase I of the Soil³ project and disseminated among experts from different disciplines. The soil ESS classification chosen for the expert survey included 16 ESS (Dominati et al., 2010), which were aligned with the CICES framework (Annex 1). For each ESS, experts were asked to grade the potential role of the subsoil in providing the service, by giving an appreciation among the following pre-fixed answers: 0 - not relevant; 1 - slightly relevant; 2 - moderately relevant; 3 - relevant; 4 - very relevant. In addition, a focus group discussion with soil experts was organized to verify, discuss and compliment the survey results.

2.2 Data to assess changes of ecosystem services

The analysis of changes in the provision of ESS as a result of mechanical subsoil loosening is mainly based on data from the central field trial (CF1) of the Soil³ project. The experiment consisted of control plots and stripwise deep tillage with the incorporation of different materials. For the assessment presented here, only data from the incorporation of compost is considered, as this variant was evaluated as the most effective to increase yields. Data on pre-crops from the Soil³ project are not available yet (CF2 and CF3). Instead, we use data from a previous project carried out on an adjacent test site with very similar site conditions, other scientific studies and/or expert opinions.

3 Results

3.1 Relevance of the subsoil for the delivery of ecosystem services

A total of 57 experts from different disciplines (agronomy, soil sciences, microbiology, soil chemistry, etc.) participated in the survey. Figure 1 shows the results based on the survey and the follow-up focus group discussion with selected experts. For further analysis, only those ESS will be considered which, on the one hand, have been assessed as 'very relevant' or 'relevant' and, on the other hand, play a role in the agricultural production system.

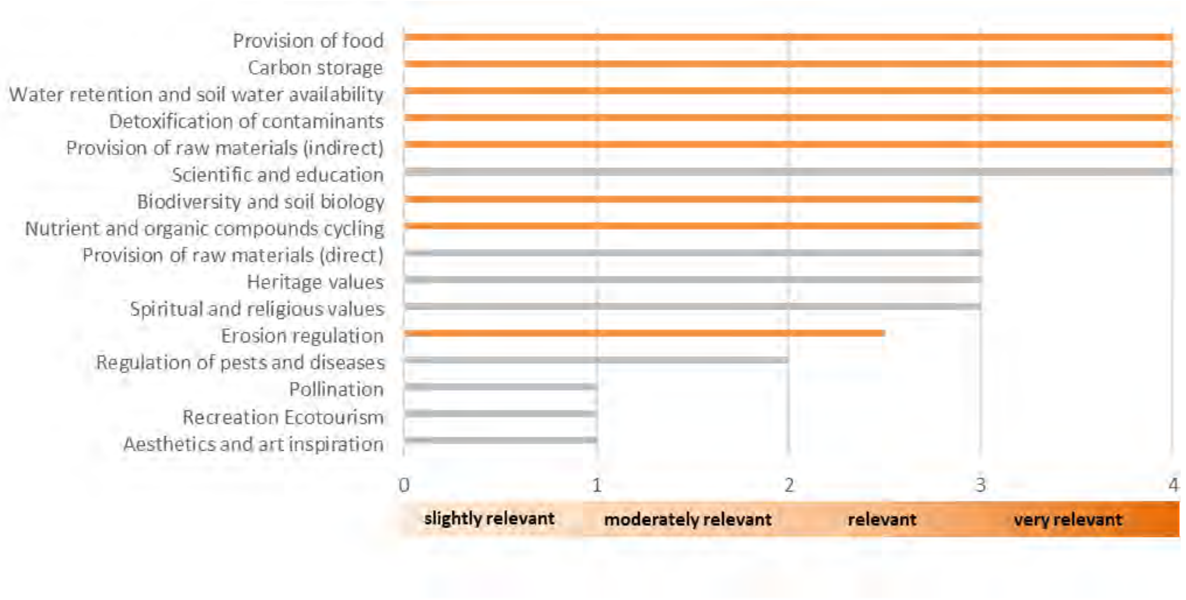

Figure 1: Expert assessment of the importance of various ecosystem services in relation to the subsoil. ESS that are relevant in the agricultural production system are highlighted in orange.

Provision of food, feed and fiber

In the above mentioned survey, the provision of food and the provision of other indirectly provided raw materials such as fiber or biofuel crops were assessed separately. In the following analysis, we summarise all crops into one category regardless of their use.

Soil is a physical support for growing crops (including feed crops and non-food crops for bio-based industrial products and biofuels) and it supplies them with nutrients and water. There is an overall agreement among the experts on the high relevance of the subsoil for food provisioning. Experts pointed out that the subsoil generally has more relevance for providing water to crops, rather than for providing nutrients, as they are found in lower concentrations in the subsoil compared to the topsoil. Moreover, experts remarked that the subsoil's contribution to the provision of food is dependent on various factors, such as soil and crop type.

As the subsoil is harder to access by plants, it might become a relevant resource only in case plants do not find satisfying growing conditions in the topsoil. Particularly, the subsoil is believed to be the "insurance of the plants" when the topsoil cannot provide sufficient resources for plant growth (expert statement). The expert judgment is consistent with recent research findings, which point to the potential of the subsoil for increasing crop resistance to extreme climate events, specifically under extreme drought conditions when water stocks are insufficient in the topsoil or under poor soil quality and low fertilization farming systems (Gaiser et al., 2012; Kautz et al., 2013).

Carbon storage

For carbon sequestration, experts agree on a high relevance of the subsoil. Despite lower concentrations, approximately half of the soil carbon is assumed to be located in subsoils. It is argued that the subsoil has a high potential to store (more) carbon due to its large volume. Furthermore, it is argued that the subsoil provides better stability to soil organic matter in contrast to the topsoil and is thus better suited for long-term carbon storage. The scientific literature on the topic largely mirrors the experts' opinions (Harrison et al., 2011; Lorenz & Lal, 2005; Powlson et al., 2011, Chabbi et al., 2009; Rumpel et al., 2012).

Water retention and soil water availability

Soils have the capacity to store water, thereby regulating water flows (freshwater levels, supply and discharge) and mitigating flooding. Overall, experts agree on the relevance of the subsoil for contributing to water regulation. Thanks to a higher volume, the subsoil has a larger capacity to store water and is less impacted by climatic events. However, experts differentiate between water storage and drainage, sometimes stressing that the latter happens more often in the subsoil because of the lack of soil organic matter, responsible for the sorption capacity. Thus, water retention might be less efficient in the subsoil but, thanks to its volume, the overall capacity of retention is much larger than in the topsoil.

Detoxification of contaminants

The soil absorbs (physically and chemically) or degrades harmful compounds and contaminants (such as E. coli or harmful substances from pesticides), thereby avoiding their release in water bodies.

Overall, the subsoil's contribution to this ESS is relevant. Subsoil is particularly presented as the "last filter" before groundwater. Nevertheless, the processes at stake are still largely unexplored and experts disagree on whether the subsoil rather absorbs contaminants or degrades them. In this context, the microbial degradation potential of the subsoil is poorly explored. However, it is known that many contaminants are transferred to the subsoil (sometimes even directly from the surface through macropores). It is argued that even if microbial density in the subsoil is lower than in the topsoil, degradation processes in the subsoil are crucial to prevent leaching of contaminants to the groundwater. Specifically, some highly specialized microbial communities, which rely on alternatives to carbon and thus prosper in the hard conditions of the subsoil, might be the only ones capable of degrading certain complex organic compounds. Badawi et al. (2013) even argue that, under specific conditions, active subsoil biopores might contribute to pesticide mineralization.

Biodiversity and soil biology

Soil provides various ecological niches with different environmental conditions, offering habitats for plant and animal nursery and reproduction.

The low number of expert comments and their content reveal that little is known about biotic diversity in deep soil layers. Foxes, anecic earthworms, bacteria and a number of insects might use the subsoil as their habitat, but the general agreement is that the greatest soil biodiversity is found near the surface, where there is enough renewal of organic matter and nutrients, which are essential for soil organisms. However, experts pointed out that subsoil provides adverse environmental conditions, which enhance community differentiation (C-limited communities). Particularly, microbiologists are the first ones to assume that the subsoil could be a "reservoir of microbial diversity" with specialized and possibly unique micro-organisms or fungi. For certain communities, the environment might even be more favorable for development as subsoil offers more stability and less interactions with surface perturbations. Moreover, hotspots of organic matter are a very promising structure in terms of biodiversity development.

Nutrient and organic compound cycling

This ESS encompasses soil processes that maintain and provide soil fertility by recycling dead organic compounds and nutrients.

The relevance grade could not be determined by the results and experts indicated that there is a knowledge gap regarding nutrient cycling in the subsoil[1]. There is a wide agreement among the experts that overall, the topsoil has a more important role for this ESS. Particularly, the recycling process is slower in the subsoil as there is much less input of dead organic matter into the subsoil and a lower temperature. Some experts even stated that the subsoil acts like a sink of nutrient and organic compounds rather than a part of the cycling process. Yet, microbiologists advanced that subsoil might contain a lot of nutrients which could be mobilized by subsoil biodiversity. The cycling of nutrients depends on the input of organic matter, which can be transported to the subsoil through the action of anecic earthworms or roots, particularly in biopores. Biopores as subsoil "hotspots" play an important role for the delivery of this ESS: in these patches of higher SOM and microbial activity, organic matter is transported downwards by anecic earthworms and plant roots, from which plant-available nutrients are generated at much higher rates than in the surrounding bulk soil, and transported back to the topsoil via plant uptake.

Erosion regulation

Vegetation coverage and soil structure and integrity stabilize land and avoid its deterioration caused by erosion. Regarding the contribution of the subsoil, expert opinions ranged over all possible gradings: one

[1] The Soil³ project contributes to closing this knowledge gap.

third of the survey participants graded "very relevant", another third opted for "slightly relevant" or less. Comments show that experts perceive the issue differently. While erosion is clearly a phenomenon that occurs at the surface, some experts pointed out that the topsoil is not the only part to consider for erosion regulation. In fact, soil erosion is often caused by compacted subsoils, which are unable to regulate water flows anymore. Under this assumption, a healthy subsoil is a condition to erosion mitigation, which makes the subsoil particularly relevant for the provision of this service.

3.2 Defining ecosystem services and related indicators

For all relevant ESS, appropriate indicators were identified based on the investigated soil parameter within the Soil³ project. These indicators are used to assess changes in ESS resulting from subsoil management measures. Table 1 lists all key ESS, associated Soil³ activities and derived indicators.

Table 1: ESS, related activities within the Soil³ project and derived indicators

Ecosystem service	Related Soil³ activity	Indicator
Provision of food, feed and fiber	*Research activity 7230: Long-term effects of subsoil manipulation on crop yields (UB-PB)*	Yield [dt/ha]
Carbon storage	*Research activity 2320: Organic matter (old subsoil management) (TUM-BK)*	C content [C/ha]
	Research activity 6320: Carbon and nutrient patterns (TUM-BK)	
Water retention and soil water availability	*Research activity 6210: Monitoring of 3D water distribution on the test sites (FZJ-IIb)*	Water content [%]; macroporosity [%]
	Research activity 7120: Water dynamics on the test sites (UB-PB)	
Detoxification of contaminants	*Research activity 6160: N_{min}-Monitoring on CF1 and CF2 (UB-AOL)*	N_{min} [kg/ha]
	Research activity 8510: N- Leaching on CF1 and CF2 (UB-BK)	
Biodiversity and soil biology	*Research activity 2250: Reverse Transplanting of bacteria* *Research activity 1240 Reconstruction of microbial nutrient cycles, especially N and P (TUM-MIK)*	Microbial biomass [µg/g] Gene copy number [copies/g]
	Research activity 2310: Earthworm and biopore density of treposols (UB-AOL)	Earthworm abundance [n]
Nutrient and organic compounds cycling	*Research activity 7150: Effects of melioration measures on nutrient uptake (UB-PB)*	Nitrogen (N) /Phosphorus (P) uptake [kg/ha] Soil N_{min} [kg/ha]
	Research activity 6160: N_{min}-Monitoring on CF1 and CF2 (UB-AOL)	
	Research activity 8510: N- Leaching on CF1 and CF2 (UB-BK)	
Erosion regulation	*Research activity 7140: Effects of melioration measures on soil structure and root growth (UB-PB)*	Infiltration [mm/h]
	Research activity 6170: Biopore density on CF2 (UB-AOL)	Biopore density [n/ha]

The quantification of yields is a well-suited indicator for evaluating changes in the **provision of food, feed and fiber**. With higher yields, the limited arable land is used for food, feed and fiber provision more efficiently. Yield varies with the site (e.g. soil type) and weather conditions. Likewise, the effects of certain measures can vary according to site conditions. Therefore, yield comparisons from multiple sites and several years are necessary to evaluate the effectiveness of subsoil management.

An increase in soil carbon content after the application of certain subsoil management measures indicates that more **carbon** is **stored** in the soil, which would otherwise be released into the atmosphere and contribute to global warming. However, to ensure that this increase truly indicates a contribution to mitigating climate change, it is important that the carbon stored in the soil is additional sequestered carbon and not just carbon that is moved into the soil from elsewhere. Furthermore, it is important to ensure that the additional sequestered carbon remains in the soil, i.e. that higher carbon levels can be detected not only in the first year after the measure is applied, but over many years.

With regard to **water retention**, a distinction must be made between the soil property of allowing water to move through the soil and the soil property of storing water. Water retention can be quantified due to water conductivity, which relates to how fast water passes from the surface to deeper soil layers and can be increased by continuous coarse-pored structure and higher macroporosity. However, in agricultural systems **plant water availability**, e.g. the number of water-holding pores, plays a major role as well. Plant water availability is influenced by the soil type and can be changed by the addition of compost or by changing soil bulk density. The water supply to the following crops may be influenced by changes in macroporosity inducing higher root growth.

When soil is compacted, water cannot percolate to deeper soil layers, and after high rainfall events water stays on the surface, producing runoff and **water erosion**. Therefore, measures mitigating subsoil compaction can also contribute to reducing erosion by water. However, the indicator penetration resistance or the presence of continuous biopores indicates only the potential for mitigating erosion, other factors in the topsoil and site characteristics such as slope inclination are crucial here.

Soil biodiversity can be assessed through the diversity of soil life, but habitat quality can also provide an important indication of potential soil life. Higher earthworm abundance directly measures the effectiveness of the proposed measures with respect to habitat quality for earthworms. It is important to note that there are different earthworm types with different habitats (epigeic, endogeic and anecic earthworms), and the proposed measures may affect individual earthworm types differently. Conclusions on habitat quality can also be drawn from the amount of microbial biomass. Conclusions about diversity cannot be made directly based on these data.

With regard to plant nutrients, the **nutrient cycles** of N and P play an essential role in agricultural systems. N uptake from the subsoil is difficult to measure. However, it is possible to estimate the percentage of N taken up from the subsoil by modelling. Also, it was possible to label biopore walls with ^{15}N and determine nutrient uptake from biopore walls. The P uptake from the subsoil can also be estimated by modelling procedures.

The ability of a soil to retain pollutants and thus contribute to the **detoxification of contaminants** depends on the soil type, humus content and soil life. Quantifying the retention potential of soil for pollutants is not a focus of the Soil³ project. However, N leaching through the incorporation of compost or through the cultivation of N-fixing precrops can play an important role in relation to groundwater pollution. High Nmin values in the subsoil indicate a high potential for nitrate leaching, especially in times without crop roots in the deep soil layers.

3.3 Changes in ecosystem services resulting from subsoil management

Table 2 summarizes changes in ESS derived from the evaluated indicators based on field experiments within the Soil³ project and other scientific publications. The results show that both subsoil management options – biological subsoil melioration and stripwise subsoil loosening with the introduction of organic material – lead to a change in the provision of soil-related ESS. With the exception of the effect on potential N-leaching both measures have an overall positive effect on considered ESS.

Table 2: Changes of soil-related ESS resulting from subsoil management

Ecosystem service	Indicator	Subsoil management technique	Change in %	Year after manage-ment	Source
Provision of food, feed and fiber	Yield [dt/ha]	Soil³ method	+ 20%	1/2/3	Jakobs et al. (2019) Soil³ project CF1 (unpublished)
		Deep-rooted precrops	+ 5%	1	Soil³ project CF2 (unpublished)
Carbon storage	C storage [C/ha]	Soil³ method	+ 14%	1	Soil³ project CF1 (unpublished)
		Deep-rooted precrops	+ 4-5%	1	Athmann (unpublished)
Water retention and plant water availability	Macroporosity [%]	Soil³ method	*Results are expected in the further course of the project*		
		Deep-rooted precrops	+ 300% higher macroporosity + 118% higher water uptake from 90-105 cm soil depth	1 1	Gaiser et al. (2012) Uteau et al. (2013)
Detoxification of contaminants	N-leaching	Soil³ method	Year 1: +75% Year 2: + 73%	1/2	Jakobs et al. (2019)
		Deep-rooted precrops	Year 1: + 83% Year 2: + 61%	1/2	Seidel et al. (2019)

Table 3 continued: Changes of soil-related ESS resulting from subsoil management

Ecosystem service	Indicator	Subsoil management technique	Change in %	Year after manage-ment	Source
Biodiversity and soil biology	a) Earthworm abundance b) microorganism	Soil³ method	a) - 48% less anecic earthworms, but 100% higher abundance of others b) -100% nitrate after green manure and straw addition; + 400% $N_{mic;}$+ 3-times *nosZ* gene abundance compared to control	a) 54 b) 30 days	a) Athmann unpublished b) Jaiswal, Schulz (Soil³ project; unpublished)
		Deep-rooted precrops	a) 3-fold increase of earthworm abundance b) 2-fold increase of microbial biomass		a) Sohlenius (1990) b) Haynes (1999)
Nutrient and organic compounds cycling	N-uptake [kg/ha] /P-uptake [kg/ha]	Soil³ method	N: Results are expected in the further course of the project P: + 30%	2	P: Braun et al. (Soil³ project; unpublished)
		Deep-rooted precrops	N: + 20-50% P: 0 %	1	Seidel et al. (2019)
Erosion regulation	Large size biopores	Soil³ method	*Results are expected in the further course of the project*		
		Deep-rooted precrops	+ 20% higher densities of large sized biopores > 2 mm diameter	2/6	Kautz et al. (2010), Han et al. (2015)

Provision of food, feed and fiber Both considered subsoil management options have a positive yield effect. Mechanical subsoil loosening with the incorporation of compost has resulted in an increase in yield of between 19% and 36% on average in three consecutive years (2017, 2018 and 2019). Only in the last year fertilizer was applied in the usual amount, resulting in yields of 11.3 t/ha of winter barley. This is on average 2.4 t/ha more than on the control site. First results of CF2 also show a positive yield effect of lucerne on the following crop of 3-6% in comparison to field grass. On an adjacent test site in a previous project, yield increases after lucerne ranged in-between 14 and 25% compared to fescue (Seidel et al. 2019). However, it should be noted that these results are only from two experimental years and only one site and that there was no control without precrops. More years and more sites are needed to assess a long-term effect.

Carbon storage

The results from CF1 show that deep loosening of soils in the top 50 cm, together with the incorporation of compost, resulted in an increase in SOC stocks of about 14% in the top one meter. Compared to the control, an increase of 10 t C/ha could be measured on average. However, this increase was detected with enough confidence only in the layer that received the organic amendment in the top 50 cm. Here, an average increase of 30% could be measured, whereas a decrease of about 15% was detected in 50-100 cm. The data show a high variability between the measurements, therefore further investigations are necessary. Investigations of the effect of cropping lucerne on carbon stock from an unpublished field trial on an adjacent experimental plot showed an average increase of 4% C from the first to the second year and an increase of 1% from the second to the third year (year 1: 1260 t C/ha; year 2: 1309 t C/ha; year 3: 1327 t C/ha)

Water retention and plant water availability

In terms of subsoil loosening with the incorporation of compost, only the gravimetric soil water content was measured on the test sites of the Soil³ project. In general, soil water content decreased with soil depth and throughout the cropping season. In comparison to the control, lower water content in 70 cm soil depth was shown, i.e. directly underneath the compost. Below that, the water content increased slightly again. This could be an indication that the water percolates faster due to the loosening of the subsoil. Further investigations on water content and infiltration into the soil are needed. The investigations will be carried out in the further course of the project. Findings from an adjacent site show that after one year of cropping lucerne, macroporosity at 90 cm depth was higher than after other precrops (17.8% vs 4.4%, Uteau et al. 2013), and the following crop spring wheat soil water uptake was shifted to deeper soil layers after lucerne as compared to other precrops (3.5 vs. 1.6 mm water extracted from 90-105 cm, Gaiser et al. 2012). The macroporosity was increased by 300% and the spring wheat water uptake was 118% higher from 90-105 cm soil depth after precrop lucerne compared to precrops fescue and chicory (Gaiser et al. 2012). Lucerne was compared to other fodder crops, there was no control without fodder crops (control). It is expected that the changes would be even more pronounced if a control treatment was included.

Detoxification of contaminates

Both mechanical subsoil loosening with compost incorporation and biological subsoil melioration with leguminous precrops led to higher N_{min} values in the subsoil. In the first year after the technical melioration, N_{min} from 50-100 cm in spring was 75% higher compared to the control (91 kg vs. 23 kg, Jakobs et al. 2019). In the second year after the melioration, the increase was in a similar range (75 kg vs. 20 kg). After two years of cropping lucerne on an adjacent site, N_{min} from 45-105 cm was 83% higher compared to cropping oats followed by fescue (42 kg vs. 7 kg). In the second year the difference between both precrops decreased while N_{min} in total increased (66kg vs. 26 kg).

Biodiversity and soil biology

There is no data on the effect of subsoil loosening with the incorporation of compost on earthworm diversity and abundance within the Soil³ project so far. With regard to the effect of one-time deep ploughing (treposols) and thus the incorporation of organic matter into the subsoil, a decrease of anecic earthworms by 48% on average and an increase of 100% of other species (epi- or endogaeic) after 54 years was observed (Athmann unpublished). Experiments carried out on an adjacent site to the Soil³ CF1 and CF2 have shown that two or three years of fodder cropping resulted in significant increases of around 300% of anecic earthworm abundance (Kautz et al. 2014).

In the frame of a short-term incubation experiment (30 days) with the soil from CF1 and the same organic material as used in the field experiment (straw, green manure), a complete loss of nitrate in subsoil was observed 30 days after the addition of organic material to the sub soil. On the one hand, this was accompanied by an increase of N_{mic} of 400 to 500% in the straw and green manure treatment, respectively, while C_{mic} only doubled. On the other hand, the general increase of the bacterial abundance also caused an increase of the denitrifying community, which favors nitrate reduction to gaseous end products. Especially bacteria carrying the *nosZ* gene, which enables a complete denitrification to N_2, increased stronger (16 times) in the straw treatment then the overall bacterial community, which only increase by a factor of 6. In contrast, green manure addition hampered the growth of the denitrifying community compared to whole bacterial community, which increased by a factor of 9, while the *nosZ* community only by a factor of 3 compared to the control treatment.

Nutrient and organic compounds cycling

The results of the N uptake analysis within the Soil³ project are expected in the further course of the project. On an adjacent site, after two years of lucerne cultivation, spring wheat absorbed 134 vs 108 kg N/ha in 2010 and 163 kg N/ha vs 86 kg N/ha in 2012 as compared to the reference preceding crop fescue. This corresponds to an increase between 19% and 47% (Seidel et al. 2019).

Two years after deep loosening with incorporation of compost, contents of plant-available P in topsoil were similar close to and distant from the furrow and in the control treatment. In shallow subsoil (30-50 cm), contents of plant-available P were significantly higher close to than distant from the furrow and in the control treatment (46.1 vs. 20.8 and 15.3 mg/kg). Over the whole profile (0-100 cm), contents of plant-available P close to the furrow were 38.1 mg/kg higher than distant from the furrow and 37.0 mg/kg (30%) higher than in the control treatment (Control treatment, 0-1 m: ca. 124 mg/kg). The high standard error of the mean especially in 30-50 cm depth is caused by the management technique (and general heterogeneity in subsoil); data show just the moment of flowering. On an adjacent site, the provision of P from the subsoil was hardly influenced by cropping lucerne (Seidel et al. 2019).

Erosion regulation

The extent to which the subsoil loosening with the incorporation of compost has an effect on soil loss was not directly investigated. Investigations on infiltration during heavy rainfall events will be carried out in the further course of the project and can probably be used to assess the erosion effect. Precrop treatments have no effects on overall penetration resistance, but on an adjacent site, 20% higher density of large-sized biopores after lucerne as compared to a fibrous rooted precrop as paths with zero penetration resistance for roots of following crops were measured (Han et al. 2015).

4 Discussion and Outlook

A central objective of this paper was to summarize relevant soil parameters that have been generated in various activities of the Soil³ project. These data form the core of a forthcoming cost-benefit analysis, which will assess the societal cost and benefits resulting from subsoil management measures. A precondition for such a cost-benefit analysis is the availability of robust data on the effects of alternative subsoil management measures on soil-related ecosystem services.

Schulte et al. (2014) provide a conceptual framework for the quantification of soil-based ESS / soil functions in an agricultural context and summarize these as a) production of food, fibre and (bio)fuel, b) water purification, c) carbon sequestration, d) habitat for biodiversity and e) recycling of (external) nutrients/agro-chemicals. The results of the expert survey and focus groups discussion implemented in the context of the Soil³ project show that, according to experts, the subsoil plays an important role in the provision of these ESS.

Within the Soil³ project, different soil parameters are investigated, which can be used to assess changes in ESS resulting from subsoil management measures. The results shown here relate to changes in ESS after one year in the case of mechanical loosening and after two or three years in the case of pre-crop cultivation.

In general, the provision of soil-related ESS depends not only on the management of the (sub) soil, but also on the soil type and climatic conditions. Most of the results relate to only one or two experimental years and only one site. The data are therefore only a first indication of how the provision of ESS might change as a result of the considered subsoil management options. In order to make reliable statements, further years and more sites will have to be investigated. A validation with forthcoming results of the test sites CF2 and CF3 is planned.

Furthermore, to explore the extent to which regional differences such as weather conditions and different soil types influence the effects of subsoil management and thus the provision of ecosystem services, a comparison of CF2 and CF3 is necessary. The results of CF2 and CF3 are not expected before 2022.

In the following, the individual indicators that serve to evaluate the considered ESS are discussed:

Provision of food, feed and fiber

Studies have shown that the loosening of deep soil layers can stabilize or even increase yields (Schneider et. al, 2017; Schjønning et al., 2015; Leskiw et al., 2012; Evans et al., 1996). These yield effects can be attributed to improved root growth and thus to increased nutrient and water uptake (Cai et al., 2014). The cultivation of deep-rooted pre crops, which promotes biopores, can also have a positive effect on the water and nutrient supply for plants (Landl et al., 2019; Gaiser et al., 2012). While effects can be achieved quickly with mechanical processing, the long-term effects in particular are controversially discussed (Schjønning et al., 2015; Kautz et al., 2013; Leskiw et al., 2012; Munkholm et al., 2005; Evans et al., 1996). The results of the Soil³ test fields show that mechanical subsoil loosening with incorporation of compost has led to significant yield increases for three years in a row (Jakobs et al., 2019). In the further course of the project, it will be investigated whether the disadvantages of mechanical intervention in the soil can be avoided by adding compost to the subsoil.

Carbon storage

Amounts of organic matter in agricultural soil (SOM) are responsible for several ecosystem services, such as fertility and food production, maintenance of biological activity and diversity, water holding capacity, and climate regulation (Wiesmeier et al. 2020; Smith et al. 2015; Tilman et al. 2002). The amounts of SOM and its persistence are controlled by edaphic constraints, such as climate, lithology and soil type, or topographic position. However, in agricultural soils, these amounts are also controlled by the management practices and their history (Wiesmeier et al. 2020; Mayer et al. 2019). Despite higher concentration in topsoil, a considerable fraction of SOM is present in deeper horizons and thus an assessment of a specific management strategy on OM stocks has to take subsoil into account. It is well-known that organic fertilization supports higher levels of organic matter in agricultural soils, but it has been studied almost exclusively in the top 30 cm layer. However, the decomposition of organic material can be hampered at greater depth, due to lower temperature and oxygen availability, and organic amendments in the subsoil are thus expected to persist longer. Detecting and quantifying potential change in SOM contents in subsoil is very challenging because of the low C concentrations and of field heterogeneity.

Deep loosening of soils in the top 50 cm, together with incorporation of compost, resulted in an increase in SOC stocks in the top one meter. However, this increase was detected with enough confidence only in the layer that received the organic amendment and did not necessarily correspond to C sequestration in the long-term, but to the persistence of the amendment at the timescale of sampling. The monitoring of this experimental field over several years is necessary to be able to make an appropriate assessment of the influence of the different treatments on the SOC stocks and thus the climate mitigation potential.

Fodder crops, especially lucerne, provide large amounts of carbon via root debris and exudates (Hafner and Kuzyakov 2016). In field trials of the Soil³ project, about 4% higher carbon levels were measured after three years (as compared to one year) of perennial fodder cropping. However, based on SOC analyses in long-term experiments with different crop rotations, Powlson et al. (2018) concluded that a shift to an arable-ley system with 8 years perennial fodder cropping and only 2 years of annual crops would be necessary for a persistent build-up of SOC.

Water retention and plant water availability

One of the main soil functions is to store soil water and supply it to plants. Plant available water is defined as the water held between field capacity and wilting point within the rooted soil layers. The soil hydraulic properties and thus the plant available water capacities depend on parameters such as soil texture, organic carbon content, porosity and soil bulk density (Wösten et al., 1999). The soil water holding capacity is influenced by the amount of water holding pores, which in turn is influenced by soil type. Water conductivity relates to how fast water passes from the surface to deeper soil layers and can be increased by higher macroporosity. Plant available water to following crops may be influenced by changes in macroporosity inducing deeper rooting. The soil hydraulic properties can be changed by the addition of compost or by changing the soil bulk density as well as by deep rooting precrops.

It is assumed that mechanical soil loosening together with the incorporation of compost has an effect on the pore size distribution and thus also on the water holding capacity. This could not be assessed by means of the previous investigations. With the planned infiltration tests planned in the further course of the project, it will probably be possible to make a statement here.

Deep-rooted preceding crops such as lucerne have a positive effect on the formation of biopores and thus a potential positive effect on the percolation of water at great depths as well as on water absorption from these depths.

Detoxification of contaminates

The ability of a soil to retain pollutants and thus contribute to the detoxification of contaminants depends on the soil type, humus content and soil life. There are no studies on how the two considered subsoil management measures influence this ability. However, there is the possibility of introducing harmful pathogens into the soil through the compost. In addition, there is a risk of leaching large amounts of nitrate into the groundwater with respect to both management options.

Biodiversity and soil biology

Soil provides various ecological niches with different environmental conditions, offering habitats for plant and animal nursery and reproduction, thus promoting development of multiple microorganisms and fauna.

The subsoil is a habitat for anecic earthworms, who extend their vertical burrows into large depths and create large-sized biopores as pathways for crop roots in the densely packed subsoil. Additionally, having high oxygen contents, high plant available N and P and high microbial biomass and activity, these biopores are hotspots of plant nutrient acquisition, especially if colonized by earthworms (Athmann et al., 2017). Anecic earthworms are promoted by soil rest. The effect of the Soil³ melioration method on anecic earthworms was not measured yet. The results of Treposols indicate that the incorporation of organic matter into deeper soil layers leads to a change in the earthworm abundance of different species (Athmann unpublished[2]). However, no conclusive assessment of changes in biodiversity could be derived from these results. In their own experiments, Kautz et al. established that two or three years of fodder cropping resulted in significant increases of anecic earthworm abundance (Kautz et al., 2014).

Bacterial communities in subsoil are adapted to low oxygen and low nutrient contents and are mostly oligotrophic (Uksa et al., 2015). The addition of organic material alters the conditions in the subsoil habitat substantially by increasing the amount of easily available nutrients but also soil structure and redox conditions. Similar to other nutrient hotspots in subsoil like drilosphere and rhizosphere (Uksa et al., 2014), this caused a strong increase in microbial abundance in general and of the denitrifying community in particular. Thus, the high nitrate losses observed in our short-term experiment might be due to immobilization in the microbial biomass or by gaseous losses. To proof those assumptions, we will also measure transcription of the respective genes and long-term effects on the denitrifying community in frame of the field experiment. Those samples will be analyzed in the further course of the project. Moreover, it needs to be proved whether and when the N immobilized in the microbial biomass will be released again, as we did not observe an accumulation of NH_4 during the time course of our experiment. Future studies should also consider actual N_2O measurement to identify drivers for N_2O emission after subsoil melioration.

Nutrient cycling and organic compounds cycling

Nutrients in soil are required for ecosystem services such as soil fertility, plant growth and food production. Nitrogen (N) and phosphorus (P) are two of the essential macronutrients. Arable subsoils are estimated to contribute considerably to plant nutrition, varying between 30 and more than 80% for total P supply and between 9 and 75% for N supply (Kautz et al., 2013). Therefore, the evaluation of agricultural management techniques has to take subsoil into account.

Soil P is controlled by soil parent material and can be very high, whereas only a minor portion of total P exists in a form that can be taken up by plants. In agricultural soils, P is therefore added as fertilizer, so that P contents of agricultural topsoils depend mainly on fertilization. N is essential both for increasing crop yields and protein contents. There are three forms of soil N: organic N compounds, ammonium (NH_4^+) ions and nitrate (NO_3^-) ions. Only NH_4^+ and NO_3^- ions (summarized as N_{min} or mineralized N) are directly plant available. The organic N compounds are chemically bound in plant residues, soil organic matter, or living or dead soil animals and microbes. This N is not directly available to plants, but can be converted to NH_4^+ and NO_3^- by microorganisms. In plant-available form, N is highly mobile and can thus be lost from the soil mainly via leaching into the groundwater, but also via denitrification (gaseous losses to the atmosphere, e.g. in form of N_2O).

Organic amendments are known to increase soil fertility *via* soil structure and pH. Deep loosening of soils in the top 50 cm, together with admixing of bio-compost, did not increase contents of plant-available P

[2] The results are based on data collected within the Soil³ Project in Banteln (Lower Saxony). Here treposols were investigated 54 years after the soil intervention.

in topsoil, but enhanced contents in the shallow subsoil (30-50 cm) significantly. These changes were detectable only close to the furrows filled with bio-compost, not distant from the furrows. Deep loosening in combination with bio-compost can thus provide optimum conditions for crop growth. However, fluctuation of contents of plant-available P due to the different growth stages make a long-term monitoring necessary.

Deep loosening with bio-compost markedly increased soil N_{min} contents throughout the soil profile. While this coincided with higher crop yields and protein contents, N losses through leaching and possibly also gaseous losses through denitrification may cause environmental problems and need long-term monitoring. When legumes, namely lucerne, are grown as precrops, there are also considerable increases in soil N_{min}, with similar effects on crop yield,protein content and leaching potential. Subsoil biopores generated by anecic earthworms or taprooted perennial crops contain elevated amounts of plant available N and are an important source of N for crops as has been shown with tracer experiments, even though, due to their small volume, they contain only a small portion of total soil N. Similarly, subsoil biopores contain increased amounts of plant available P; however, the contribution of subsoil biopores to total plant P uptake is not known.

Erosion regulation

The extent to which the subsoil loosening with the incorporation of compost has an effect on soil erosion was not investigated within the Soil³ project. Whether soil erosion actually occurs depends, beside soil cover and field size, in particular on slope steepness. In general, the described mechanical subsoil management is not suitable for steep slopes due to technical issues. On slight slopes, the measure could have a positive effect if a higher infiltration can be verified on the loosened strip and the loosening is done transverse to the slope. Investigations on infiltration during heavy rainfall events will be carried out in the further course of the project.

It is well known that perennial deep-rooted previous crops have a positive effect on the prevention of erosion on the one hand through the continuous soil cover, the positive effect on the structure of soil aggregates and the formation of biopores. With regard to the prevention of erosion, biopores can play a role, especially if they extend continuously from the soil surface to the subsoil. It should be noted that this effect only lasts particularly until the field is ploughed, which farmers do before the main crop is cultivated.

Acknowledgment

The authors would like to thank Kelly Gouhoury for her great help in implementing the expert survey on the relevance of the subsoil for the delivery of ecosystem services.

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ANNEX 1

Soil-related ecosystem services as explored in the Soil[3] project and correspondence with MA and CICES

Ecosystem service	MA classification	CICES classification
Food provision	Food (fodder)	Nutrition/Biomass
Direct provision of raw materials (soil materials, biological and genetic resources…)	Genetic resources, biochemicals	Materials/Biomass
Indirect provision of raw materials (materials from plants and biofuels crops)	Fiber, timber	Materials/Biomass, Energy/Biomass
Detoxification of contaminants	Water purification and treatment	Mediation of waste, toxics and other nuisances/mediation by biota and ecosystems
Flood mitigation and water retention	Water regulation	Mediation of flows/liquid flows
Erosion regulation	Erosion regulation	Mediation of flows/mass flows
Regulation of pests and diseases	Pest and disease regulation	Maintenance of physical, chemical, biological conditions/pest and diseases control
Carbon storage and climate regulation	Air quality regulation / climate regulation	Maintenance of physical, chemical, biological conditions/Atmospheric composition and climate regulation
Nutrient and organic compounds cycling	Primary production / Nutrient cycling	Maintenance of physical, chemical, biological conditions/Soil formation and composition, water conditions
Habitat for biodiversity		Maintenance of physical, chemical, biological conditions/Lifecycle maintenance, habitat and gene pool protection

Ecosystem service	MA classification	CICES classification
Pollination	Pollination	Maintenance of physical, chemical, biological conditions/Lifecycle maintenance, habitat and gene pool protection
Recreation/Ecotourism	Recreation and ecotourism	Physical and intellectual interactions with ecosystems and land-seascapes/ Physical and experiential interactions
Aesthetics and art inspiration	Aesthetic values	Physical and intellectual interactions with ecosystems and land-seascapes/ Intellectual and representational interactions
Heritage values	Cultural diversity	Physical and intellectual interactions with ecosystems and land-seascapes/ Intellectual and representational interactions
Spiritual and religious values	Spiritual and religious values	Spiritual, symbolic and other interactions with ecosystems and land-seascapes/ Spiritual and/or emblematic
Scientific and educational values	Knowledge systems and educational values	Physical and intellectual interactions with ecosystems and land-seascapes/ Intellectual and representational interactions

Previous publications

2020/4	Wiesmeier et al. CO_2 certificates for carbon sequestration in soils: methods, management practices and limitations DOI: 10.20387/BonaRes-NE0G-CE98
2020/3	Ledermüller et al. Arbeitsbericht: Verbesserung des physikalischen Bodenschutzes bei der Wirtschaftsdüngerausbringung im Frühjahr - Herausforderungen und Lösungsansätze DOI: 10.20387/BonaRes-ESZ2-NRV9
2020/2	Siebert. Energy Crops and Erosion Control in Germany in the Context of the Bioeconomy Strategy. DOI: 10.20387/BonaRes-TZKG-FNRC
2020/1	Wiesmeier et al. CO_2-Zertifikate für die Festlegung atmosphärischen Kohlenstoffs in Böden: Methoden, Maßnahmen und Grenzen. DOI: 10.20387/BonaRes-F8T8-XZ4H
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2019/4	Paul & Helming. Handbook of Soil-Related Impact Assessment. DOI: 10.20387/BonaRes-6DJM-E22M
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