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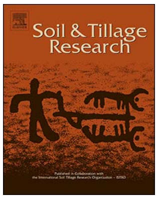

Review

The effect of deep tillage on crop yield – What do we really know?

Florian Schneider[a], Axel Don[a,*], Inga Hennings[b], Oliver Schmittmann[b], Sabine J. Seidel[c]

[a] *Thünen Institute of Climate-Smart Agriculture, D-38116 Braunschweig, Germany*
[b] *University of Bonn, Institute of Agricultural Engineering, D-53115 Bonn, Germany*
[c] *University of Bonn, Institute of Crop Science and Resource Conservation, D-53115 Bonn, Germany*

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ABSTRACT

The subsoil below the regularly tilled topsoil stores large nutrient stocks and can retain water even under drought conditions. Mechanical soil profile modifications, commonly referred to as deep tillage, could improve the plant availability of these subsoil resources. However, field studies on the benefits of deep tillage have delivered inconsistent findings. Therefore, we (i) conducted a meta-analysis of crop yield responses to subsoiling (loosening), deep ploughing (turning + loosening) and deep mixing of soil profiles, and (ii) reviewed the relationship between site properties, management practices, water availability and deep tillage-induced changes in yield. The meta-analysis was based on 1530 yield comparisons between deep and ordinary tillage at 67 experimental sites in mostly temperate latitudes. On average, deep tillage slightly increased yield (+6%). However, individual deep tillage effects were highly site-specific, including about 40% documented yield depression after deep tillage. At sites with root-restricting, mostly compacted soil layers, the crop yield response to deep tillage was 20% higher than at sites without such layers. In general, differences between deep tillage methods were less important than the presence of root-restricting soil layers. Soils with > 70% silt (labile soil structure) showed an increased risk of negative deep tillage effects. In growing seasons with dry spells, positive deep tillage effects were greater than in average years. Topsoil fertilisation buffered both extremely positive and negative deep tillage effects. Our results suggest that deep tillage increases the plant availability of subsoil nutrients, which increases crop yield if (i) nutrients are growth-limiting and (ii) deep tillage does not come at the cost of impaired topsoil fertility. On soils with stable soil structure and root-restricting layers, deep tillage can be an effective measure to mitigate drought stress and improve the resilience of crops under climate change conditions.

1. Introduction

Agriculture is facing new challenges due to climate change (Sillmann et al., 2013) and imminent supply shortages of nutrients (Cooper et al., 2011). This creates a need to access new nutrient and water sources. In cropland, the subsoil, i.e. the soil layer below the regularly tilled topsoil, can store almost 50% of total nitrogen stocks (Wiesmeier et al., 2013) and 25–70% of total phosphorus stocks (Kautz et al., 2013) and can retain water even under drought conditions (Kirkegaard et al., 2007). However, the availability of these resources to crops varies.

High soil strength often limits root propagation and thus the plant-availability of resources in the subsoil (Bengough et al., 2011). Subsoil strength tends to be naturally high because of the weight of the above soil column and internal frictional forces (Gao et al., 2016). Particularly dense soil layers of mostly pedogenic (e.g. clay illuviation, hardpan of Podzols) and, to a lesser extent, geogenic origin (e.g. soils with abrupt textural change in fluvial or tidal sediment deposits) often pose additional natural barriers for root growth. However, high soil strength can also be man-made (Batey, 2009). About 15% of the agricultural land in Europe is compacted by agricultural mismanagement (Oldeman et al., 1991). The ability of roots to propagate at high soil strength differs between crop types. Dicotyledonous annual crops tend to have thicker roots and therefore higher ability to propagate at high soil strength than monocotyledonous annual crops (Clark and Barraclough, 1999). In addition, dicotyledonous crops can improve the biopore network in the soil profile and build highways to the subsoil for subsequent crops (Kautz et al., 2013). However, today's annual cropping systems are vastly dominated by cereals and other crops with thin, fibrous roots. In soils without extensive vertical macropore channels or fissures, access to subsoil resources is thus restricted.

Mechanical modifications of soil profiles, commonly referred to as deep tillage, could alleviate high subsoil strength, facilitating deeper rooting and, thus, the plant-availability of subsoil resources. Various

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[*] Corresponding author.
E-mail address: axel.don@thuenen.de (A. Don).

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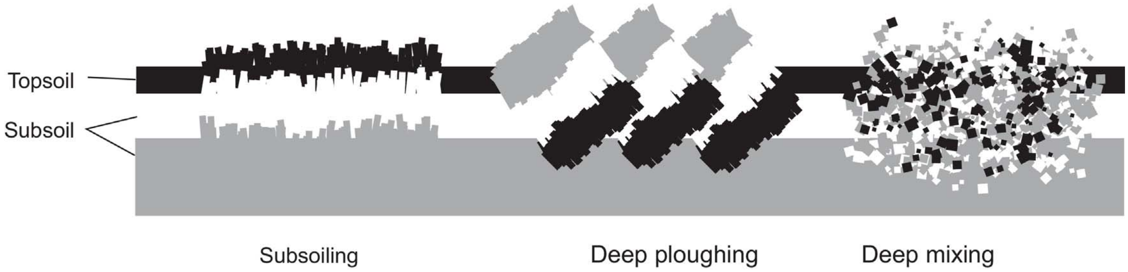

Fig. 1. Schematic drawing of deep tillage-induced changes in the soil profile.

deep tillage methods have been developed, including subsoiling, deep ploughing and complete mixing of soil profiles. Subsoiling aims at loosening the soil structure and decreasing the bulk density of the subsoil without turning or mixing soil horizons (Fig. 1, left). Subsoiling is sometimes referred to as deep ripping or deep chiselling. In contrast, deep ploughing turns soil horizons and results in complete or semi-complete inversion of the soil profile, with subsoil horizons ending up at the soil surface and topsoil horizons buried in the deep soil (Fig. 1, centre). Finally, there are deep tillage options that mix subsoil and topsoil, leading to complete destruction of soil horizons (Fig. 1, right). In the following, we refer to the latter management options as ‘deep mixing’, in order to distinguish them from mere deep ploughing (turning) or subsoiling (loosening). Deep mixing can be conducted on the whole field (e.g. with a deep rotary hoe) or in stripes with undisturbed soil in between (e.g. with a wheel-type trencher).

The notion of improving the plant availability of water and nutrients from the subsoil by deep tillage has a long history. In pre-industrial times, soil was mostly tilled with animal-drawn ploughs, which rarely tilled deeper than 20 cm (Eggelsmann, 1979), and only manual digging was able to modify the soil profile to greater depths, like the labour-intensive method of double or triple digging. However, the latter was popular in confined areas only, e.g. in central European viticulture (Mollenhauer, 2014). Between 1850 and 1960, the development of steam and combustion engines allowed the maximum ploughing depth to be increased from 20 cm to > 200 cm (Roemer, 1940; Eggelsmann, 1979). The increase in horsepower and potential tillage depth enabled reclamation of peatland by deep ploughing on a large scale in northern Germany and the Netherlands. Furthermore, large areas of Podzols, Luvisols and Stagnosols were deep-tilled in order to decrease subsoil strength. In Germany alone, more than 500,000 ha were deep tilled to break up hardpans and loosen dense illuvial clay layers (Table A1 in Supplementary materials).

In the 1970s, the popularity of deep tillage declined among both the research community and practitioners. This was presumably largely due to inconsistent yield responses to deep tillage, which failed to compensate for the high execution costs. Concerns about negative effects of ploughing on beneficial soil biota (Kladivko, 2001) also increased general resistance to the use of tillage, especially among organic farmers. Within conventional arable farming, pesticides and herbicides supported the emergence of minimum tillage systems. However, chemical pest and weed control is not the primary goal of deep tillage. The mechanical modification of the subsoil as achieved by deep tillage can disrupt root-restricting soil layers and enhance water storage, improving soil fertility in the long-term (e.g. Schröder and Schulte-Karring, 1984; Baumhardt et al., 2008). With respect to soil biota, it is important to note that deep tillage can be either performed once for ameliorative purposes, i.e. with the goal of long-lasting improvements at a given site, or annually in order to achieve gradual topsoil deepening over time. Ameliorative deep tillage may have much less negative impacts on earthworms and other beneficial soil organisms than annual deep tillage (Kladivko, 2001). In several cases, ameliorative deep tillage has even been reported to enhance earthworm activities (Borchert, 1981; Fenner et al., 1993) and increase the abundance of plant growth-promoting rhizobacteria and mycorrhizae in the subsoil (Egerszegi, 1959; Muller and Rauhe, 1959; Steinbrenner and Naglitsch, 1965).

Inconsistent yield responses to deep tillage seem to occur at different sites and with different environmental conditions (Eck and Unger, 1985). Under drought stress, deep tillage could facilitate the uptake of subsoil water and thus stabilise crop yields (e.g. Doty et al., 1975). Climate change scenarios predict an increase in the intensity and frequency of droughts in many cropping regions of the world (Olesen et al., 2011; Porter et al., 2014). Deep tillage might be a tool to make crops more resilient to climate change and mitigate yield losses caused by droughts. Furthermore, because ameliorative deep ploughing of arable land sequesters carbon (Alcántara et al., 2016), deep ploughing carries the potential to compensate for greenhouse gas emissions and, if conducted on a large scale, may contribute to meeting future climate targets. Apart from climate change, limited access to fertilisers poses an imminent threat to crop production (Cooper et al., 2011). Subsoil nutrients have been shown to sustain yield in non-fertilised trials (Garz et al., 2000). Deep tillage might further enhance the plant availability of subsoil resources. However, a quantitative overview and understanding of crop responses to deep tillage is lacking to date (Olsson and Cockroft, 2006).

We therefore conducted an extensive quantitative review of deep tillage trials. Specifically, our goals were to (i) gain a quantitative overview of documented deep tillage effects on crop yield and (ii) examine the role of site-specific properties, management practices and drought stress in determining yield response to deep tillage. Data availability delimited the focus of our study primarily to short-term effects of deep tillage on the productivity of cereal crops grown on mineral soils in temperate latitudes.

2. Material & methods

2.1. General approach

We conducted an extensive review of studies about deep tillage effects on crop yield. Deep tillage was defined for each experiment, because tillage depth changed considerably during the observation period reviewed. In general, tillage treatments were defined as deep tillage if they reached deeper than in adjacent conventionally tilled control plots. Studies with repetitive deep tillage treatments were only considered if they examined gradual topsoil deepening and their initial experimental deep tillage treatment reached into the subsoil, i.e. soil which was not tilled before. Findings from organic soils like bogs and fens were excluded because of current environmental standards on peatland conservation.

Quantitative and qualitative methods were used for data evaluation. First, a meta-analysis of experimental field trials on deep tillage was performed. This delivered a quantitative overview of deep tillage effects on crop yield. However, highly variable reporting of experimental treatments and environmental conditions restricted identification and parameterisation of the forces driving deep tillage effects. Therefore, the meta-analysis was complemented with an extensive qualitative