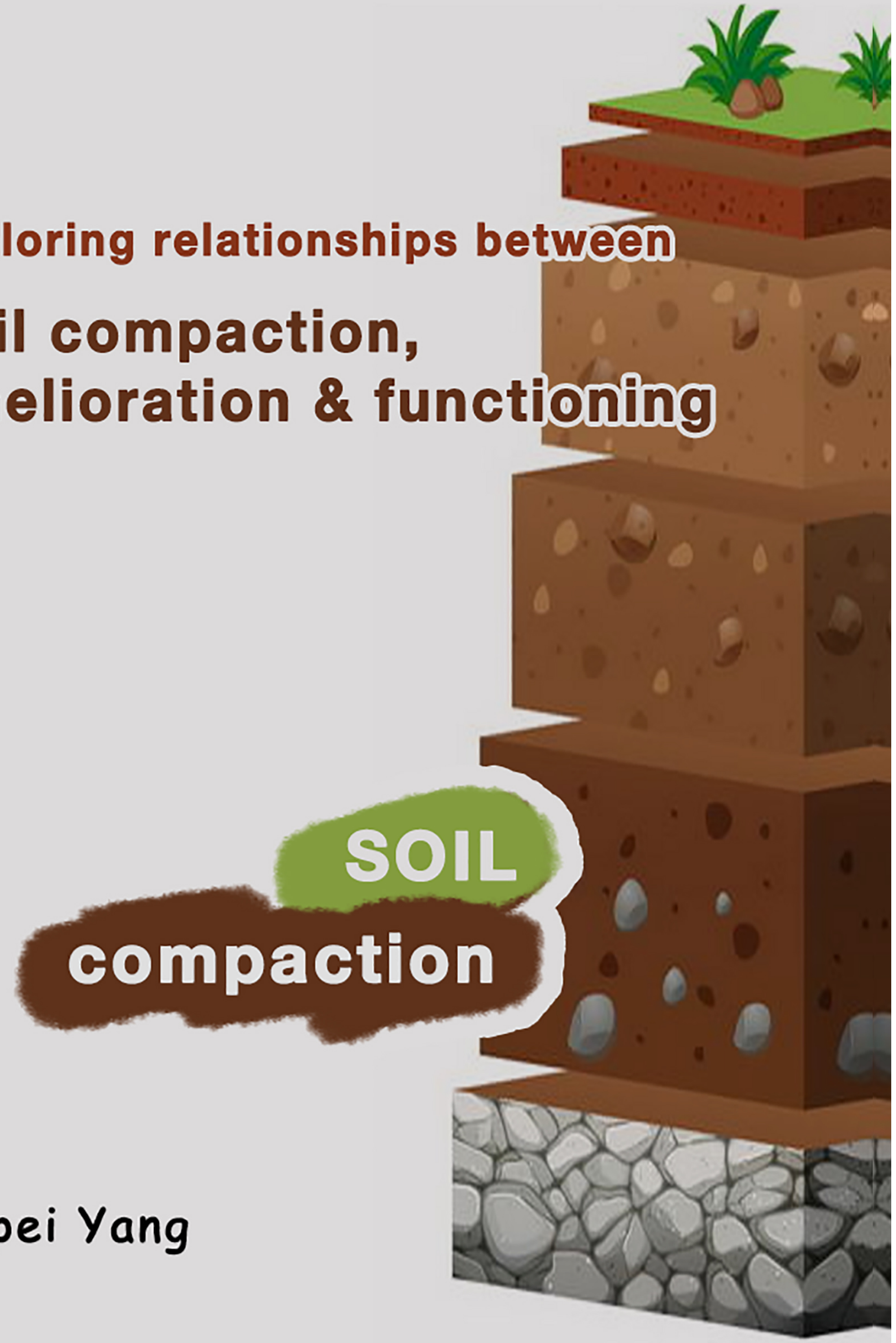
Exploring relationships between

Soil compaction, amelioration & functioning



Peipei Yang

Exploring relationships between soil compaction, amelioration & functioning Peipei Yang

Propositions

1. Prevention, amelioration and alleviation measures are equally needed and effective in addressing soil compaction.
   (this thesis)

2. Soil bulk density is an important variable at deriving N_2O emission factors for nitrogen fertilization sources.
   (this thesis)

3. The stoichiometry of carbon : nitrogen : phosphorus in substance flows is essential for building a more circular bioeconomy.

4. Small-holder farmers will remain important for rural livelihoods, but are marginalized in ways that serve no one.

5. Self-persuasion requires critical thinking.

6. Stable emotions make the world better.

Propositions belonging to the PhD thesis, entitled

Exploring relationships between soil compaction, amelioration and functioning

Peipei Yang

Wageningen, 1 November 2022

Exploring relationships between soil compaction, amelioration and functioning

Peipei Yang

Thesis Committee

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Wageningen Universiteit & Research

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This research was conducted under the auspices of the C.T. de Wit Graduate School for Production Ecology & Resource Conservation.

Exploring relationships between soil compaction, amelioration and functioning

Peipei Yang

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University,
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 1 November 2022
at 11:00 in the Omnia Auditorium.

Peipei Yang
Exploring relationships between soil compaction, amelioration and functioning
157 pages

PhD thesis, Wageningen University, Wageningen, NL (2022)
With references, with summary in English

ISBN: 978-94-6447-416-9
DOI: 10.18174/577735

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Acknowledgements of financial support

Logos are not allowed, except the FSC logo if the thesis is printed on FSC-certified paper. Acknowledgments of the cover designer and printing company are optional.

The research described in this thesis was financially supported by Chinese Scholarship Council and by the EU project SoilCare, EU grant agreement 677407.

Financial support from Wageningen University, the G. Schieter Foundation and Biomoney for printing this thesis is gratefully acknowledged.

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1 General introduction

1.1 Soil quality, functions and threats

Soil is an important natural resource; it performs vital functions for our society, economy and the environment (Blum, 2005). How well the soil is functioning is indicated by 'soil quality', as expressed by the definition of soil quality, i.e., 'the capacity of a soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation' (Greiner et al., 2017; Karlen et al., 1997). In total 7 main soil functions have been distinguished, including (1) biomass production, in agriculture, forestry and natural ecosystems, (2) storing, filtering and transforming nutrients, substances and water in soil, (3) hosting and facilitating soil biodiversity (habitats, species and genes), (4) providing a physical and cultural environment for humans and human activities, (5) providing raw materials (e.g., minerals, carbonates, sand, clay), (6) acting as carbon pool for climate change regulation, and (7) providing an archive of geological and archaeological heritage (EC, 2006).

Soil quality is largely determined by soil properties and soil or land management (Bouma, 2014). The conceptual relationships between soil properties, soil functions and ecosystem services are summarised in Table 1.1. Evidently, ecosystem services provided by the soil depend on soil functioning which depend on soil properties and land management. Soils perform the aforementioned functions simultaneously, but at different capacities, depending on soil properties, climate, environmental conditions, and land use and management (Schulte et al., 2014; Schulte et al., 2019). The complexity of soil functions and their interaction with human activities and ecosystem services have been studied for decades (Council, 2009), during which time the evaluation of soil quality has experienced large changes, in terms of objectives, tools and methods, and overall approaches (Bünemann et al., 2018). Since about the 2000s, soil biological quality, multi-functionality and ecosystem services have received much greater attention. Further, digital tools (digital mapping and big-data approaches), high-throughput analysis methods, and biological and biochemical indicators have been adopted increasingly (Barrios, 2007; Bünemann et al., 2018).

Soils in many areas of the world are vulnerable to degradation as a result of human activities and climate change. The so-called soil threats deteriorate soil properties and thereby soil functions, including the services that soils provide (Ten Berge et al., 2017). Some soil threats occur naturally, but most of these are caused by human activities, i.e., through soil use and soil (mis)management. A total of about 9 soil threats have been distinguished, depending in part on the categorization, namely soil erosion (by wind and water), soil organic matter decline and soil fertility decline, soil compaction, soil sealing, soil contamination, soil salinization, desertification, flooding & landslides, decline in soil biodiversity, soil acidification and alkalinization, (Pennock et al., 2015; Stolte et al., 2016; Tóth and Li, 2013).

Table 1.1 *A conceptual diagram linking soil properties to soil functions and ecosystem services (Adhikari, 2016).*

Ecosystem services	Soil functions	Soil properties
Biomass production	Providing food, feed and fibre; Regulating carbon sequestration; Contributing to traditions, spiritual inspiration; Supporting through primary production	Soil organic carbon; Sand, silt, clay & coarse fragments; Soil nutrients; Soil pH; Depth to bed rock; Bulk density; Available water capacity; Cation exchange capacity; Electrical conductivity; Soil porosity & air permeability; Hydraulic conductivity & infiltration; Soil biota; Soil structure & aggregation; Soil temperature; Soil mineralogy; Subsoil pans.
Storing, filtering & transforming nutrients & water	Regulating water & nutrient availability; Purification of water; Supporting ecosystem functions through water and nutrient cycling	
Hosting biodiversity	Supporting biodiversity; Regulating crop pollination, pest, & disease control; Providing pharmaceuticals;	
Platform for human activities	Supporting a human habitat	
Source of raw material	Providing minerals & soil constituents	
Carbon pool	Sequestering carbon; Regulating atmospheric CO_2;	
Storing geological & archaeological heritage	Cultural heritage values (natural science, history, anthropology); Supporting geological heritage,	

The soil threats may lead to soil degradation, which is not always easily recognizable. It has been suggested that the existing scientific knowledge on soil degradation is not sufficiently linked to land management measures and is not sufficiently implemented by end users (Bouma, 2010). Soil degradation is a global and growing concern. To better understand the cause-effect relationships of soil threats, a so-called DPSIR framework has been developed (EEA, 2000). This framework shows the relationships between (changes in) **D**riving forces in society on **P**ressures on the soil ecosystem, which affect the **S**tate of the soil ecosystem, and thereby **I**mpact the functioning of the soil ecosystem, which then invoke **R**esponses of managers and policy (Tóth and Li, 2013). The DPSIR framework (Fig. 1.1) is valuable in describing the relationships between causes and consequences of ecosystem problems (Kristensen, 2004).

1.2 Soil compaction as soil threat

Soil compaction is defined as 'The densification of soil by which total and air-filled porosities are reduced, causing deterioration of soil functions' (van den Akker, 2008). It is partly a hidden process that impairs a range of soil functions and ecosystem services (Hamza and Anderson, 2005; Nawaz et al., 2013). It has been recognised as a serious environmental problem (McGarry, 2003).

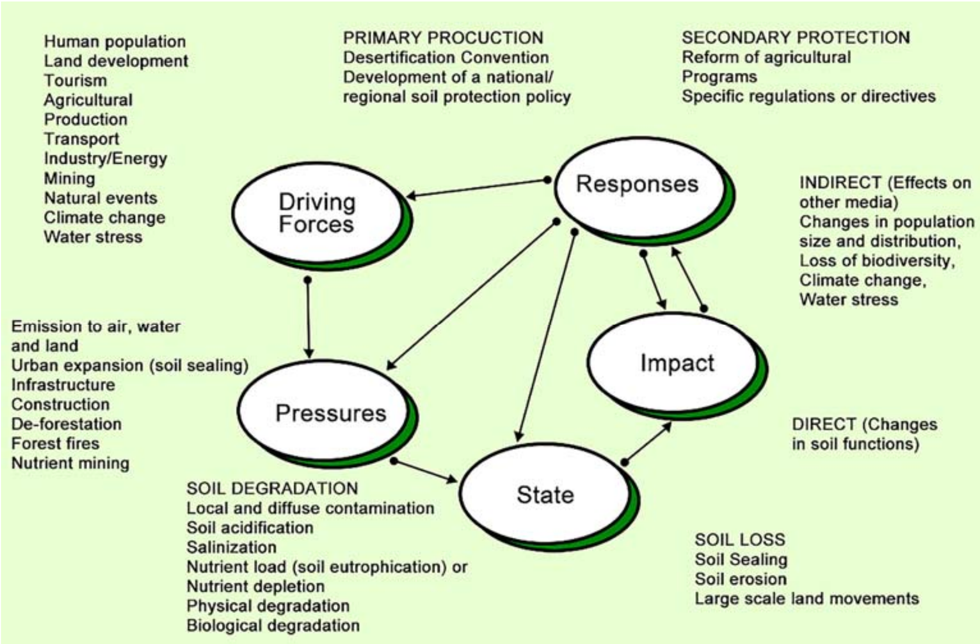


Fig. 1.1 *The driving forces – pressures – state - impact – responses (DPSIR) framework applied to soil degradation (Kristensen, 2004).*

The notion of soil compaction is known for centuries. The earliest literature links human-induced soil compaction to ploughing; research on the impacts of tillage on soil compaction started from the late 1800s (Unger and Kaspar, 1994). After World War II, more "modern" approaches on soil compaction and its alleviation were conducted (e.g., (Lutz, 1952; Veihmeyer and Hendrickson, 1948). From the 1950s, systematic research on the process of soil compaction and on the amelioration of compacted (sub)soils have been conducted in especially US (Mathers et al., 1966; Taylor, 1958), Canada (Barnes, 1971), Netherland (Van Ouwerkerk, 1968), Scotland (Soane, 1976), Norway (Njøs, 1976), Sweden (Eriksson, 1975), Poland (Domzal, 1977), China (Cheng-zhai and Wei-sheng, 1979), South Africa (Cleasby, 1964), and Australia (Arndt, 1966). Emphasis was given on defining uniform terms for soil compaction and on measurement methods for compacted soil. Also, a general theory for predicting soil compaction under wheels was formulated (Soane et al., 1980).

In 1980, the international working group on 'soil compaction by vehicles with high axle load' was established in Uppsala, Sweden. During one of its first meetings, the working formulated recommendations for maximum axle loads; i.e., an axle load of 10 t was recommended as limit (Håkansson et al., 1987). The working group discussed also results of experiments on soil compaction and designed series of new field experiments. The establishment of the working group is a milestone in soil compaction research.

In 1998, it was estimated that soil compaction had affected more than 68 million ha of agricultural land in the world, of which more than half of the area was situated in Europe (Flowers and Lal, 1998). An update of the situation in Europe in 2008 indicated that about 36 million ha of land was severely affected by soil compaction, and another 25 million ha was lightly compacted (Houšková and Montanarella, 2008). Estimations based on probability sampling suggested that about 43% of the agricultural land in Netherland had over-compacted sub-soils (Brus and van den Akker, 2018b). However, the uncertainties in these estimates is large, also because of the use of different approaches, methods and indicators for assessing soil compaction.

1.3. Causes of soil compaction

Soil compaction may be caused by natural processes and by human activities. A diversity of natural processes may lead to soil compaction (Daniells, 2012). Thus, soil compaction may happen during peri-glacial conditions, following illuviation of soil colloids in subsoil layers, through cracking and swelling processes in heavy clay soils (combined with topsoil tumbling down to the subsoil when cracks are open), through salinization and sodification, and through heavy rains and/or trampling animals. Dry-wet cycles may also lead to compaction, due to soil structural damages, e.g., changes of pore size distribution (micro-structure damage) and cracks caused by the irreversible shrinkage of pores (macro-structure damage) (Xue et al., 2014). Hardsetting soil is common in tropical countries, i.e., the soil loses part of its mechanical strength at dry conditions (Fabiola et al., 2003). Repeated freeze-thaw cycles may also lead to soil compaction through soil structure breaking down and aggregate stability reduction (Asare et al., 1999). Soils may also have a compacted subsoil because of an abrupt textural or mineralogical change with depth, due to a different geo-genetic origin (Batey, 2009).

However, the mechanization of modern agriculture and inappropriate soil cultivation and management are now seen as main causes of soil compaction. The ground contact pressure generated by field machines is the direct reason of soil compaction (Hamza and Anderson, 2005). The risk of subsoil compaction exists whenever a moist or weak soil is loaded by a moderate to high ground contact pressure on a large contact area, i.e. with a high wheel load (Alakukku et al., 2003). A vertical stress of 50kPa at 50cm depth has been suggested as a critical threshold of soil compaction when a soil is at field capacity (Schjønning et al., 2012). Based on this criterion, it has been inferred that subsoil compaction by high axle wheel loads may reach depth of 75 cm (Keller et al., 2019b). Compacted soil layers below a depth of about 40 cm are difficult to ameliorate and are therefore assumed to be virtually permanent (Håkansson and Reeder, 1994).

There are many additional factors that affect the risk of soil compaction by agricultural machines, next to the axle wheel loads. For example, the speed of the machines (Horn and Taubner, 1989), the direction of the machines (Weisskopf et al., 2000), the pace between two wheels (Håkansson and Reeder, 1994), and the number of passes (Brais and Camire, 1998) may all influence the extent of soil compaction. There is a common understanding that the more passes of the traffic, the more pressure the soil receives (Marra et al., 2018). However, a recent meta-analysis study indicated that the degree of soil compaction had no significant linear or logarithmic relationship with the number of machine passes (Ampoorter et al., 2012). This suggest that other interacting factors likely played important roles.

Soil properties, including texture, soil organic matter content, soil moisture condition, soil bulk density and soil aggregate stability also influence the risk of soil compaction. Coarse-textured soils and soils with low colloid contents are more susceptible than loamy and clayey soils (Horn et al., 1995a; Shah et al., 2017a). Soil moisture condition is critical factor in the process of soil compaction; the higher the soil moisture content, the lower the soil support capacity is, and the greater the risk of soil compaction (Medvedev and Cybulko, 1995). Stable soil aggregates protect the soil against soil compaction (Pagliai et al., 1995).

A special case of soil compaction is by animal trampling in grassland fields. The negative effects of animal trampling shows up in a loss of grass production, pasture quality and in decreases of soil hydraulic conductivity (Mitchell and Berry, 2001). Animals compact soil at rather shallow depth, between 0 and 10 cm in a loamy sand soil (Mulholland and Fullen, 1991), up to 20 cm in clay soil (Hargreaves et al., 2019). The severity of trampling induced soil compaction depends on trampling intensity, soil type (texture), soil moisture content, grass cover, and slope (Hamza and Anderson, 2005). Evidently, when the soil surface is covered with vegetation, the impact of trampling is much less (Greene et al., 1994).

1.4 Indicators for soil compaction

Most commonly used indicators for soil compaction are soil bulk density, soil strength, soil penetration resistance, water infiltration rate, and saturated hydraulic conductivity (Batey, 2009; Hamza and Anderson, 2005; Lipiec et al., 2003; Nawaz et al., 2013). However, these indicators are also criticised for various reasons; the methods for estimating these indicators are laborious, not sensitive, and indirect (proxy estimate). Huber et al. (2008) suggested four common criteria to which indicators for the identification of soil compaction should apply: a) acceptability (scientifically sound); b) practicability or measurability; c) policy relevance and easy utility; d) geographic coverage (universally applicable). They also proposed three indicators for assessing soil compaction, i.e., bulk density, air-filled pore volume, and the vulnerability to compaction. However, the indicators they proposed do not comply fully with their own criteria, as the 'vulnerability to compaction' is difficult to quantify. Vulnerability is interpreted as 'a likelihood that compaction will occur', which implies that soil moisture condition, topsoil condition, and axle loads have to be considered (Jones et al., 2003).

Lebert et al. (2007) proposed pre-compression stress and loading ratio as indicators for assessing the risk of soil compaction. These indicators need soil type specific calibration. For assessing the impairment of subsoil structure, they proposed three additional indicators, i.e., air capacity (>5% air filled porosity at a water suction of pF 1.8), saturated water conductivity (>10 cm day^{-1}), and a visual classification of the soil morphology (combination of a 'spade diagnosis' and measurements of the effective bulk density and packing density). These are all laborious measurements. Further, these authors recommended not to use soil bulk density, because of the lack of critical threshold values and an appropriate classification.

Yet, bulk density and soil porosity are direct indicators, because these links directly with the definition of soil compaction, i.e., 'the densification and distortion of soil by which total and air-filled porosity are reduced', and reflect the mechanism/process of soil compaction. Bulk density is the most frequently used parameter for soil compaction and can be measured rather easily (Panayiotopoulos et al., 1994). The limitation of bulk density measurement lies in its dependence on soil texture, soil mineralogy, and soil organic matter content. Also, soil bulk density is not a very sensitive indicator for soil compaction, and measurements are imprecise in swelling- shrinking soils (Hakansson and Lipiec, 2000).

Packing capacity is considered to be a more rigorous indicator, because it corrects for differences in soil texture (Jones et al., 2008). In situations where the soil clay content is known, packing density (PD) can be readily calculated from:

PD= D_b +0.009*C

where D_b is the bulk density in t m^{-3}, PD the packing density in t m^{-3}, C the clay content in %. Three classes of PD have been proposed: low (<1.40), medium (1.40 to 1.75) and high (>1.75 t m^{-3}), with class 'high' meaning 'highly compacted soil'.

Further, the 'relative soil bulk density', or the 'degree of compactness' has been proposed as indicator for compacted soil. The relative soil bulk density was defined as the actual dry bulk density in percent of a reference dry bulk density of the same soil. The reference dry bulk density is obtained by a standardized, long-term, uni-axial compression test at a stress of 200 kPa (Hakansson and Lipiec, 2000). Evidently, the measurements of the state of soil compaction are labour-intensive, and thus costly, especially when considering spatial within-field variations (Lipiec and Usowicz, 2018).

Soil penetration resistance is also widely used in studies and especially also in practice, because of its convenience (Stelluti et al., 1998). It reflects the 'state' of the soil, and in that sense is a direct indicator of soil compaction. The limitation of soil penetration resistance as indicator for soil compaction lies in its strong dependence on soil moisture condition (Moraes et al., 2014). Thus measurements of soil penetration resistance have to be carried out at standardized soil moisture content. This is not always the case, and explains why a large variability in penetration resistance values are often found.

Water infiltration rate and saturated hydraulic conductivity are impact indicators, because they reflect the impact of a possible densification of the soil on water infiltration and water transport in soil. These indicators reflect in part how soil compaction have changed soil functioning. These indicators are useful because of their high sensitivity to soil compaction; a small change in soil compaction may have a very strong effect on water infiltration rate and saturated hydraulic conductivity.

Crop yield is also an impact indicator, because it reflects the consequence of soil compaction for the harvested yield and thus the revenues for the farmer. The impact of soil compaction on crop yield is the result of several possible underlying causes, including distorted root growth in compacted soil, reduced water and nutrient uptake, water logging and oxygen deficiency in the root zone (e.g., (De Weerd and Klandermans, 1999; Taylor and Brar, 1991;

Unger and Kaspar, 1994)). However, many studies related to soil compaction merely focus on changes in soil properties, and not so much on crop yield (Nawaz et al., 2013), although it has been shown that impacts on crop yield may provide the economic incentives of preventive measures, including controlled traffic (Chamen et al., 2015). It cannot be excluded that the lack of adequate information on the relationship between soil compaction and crop yield in practice, is one of the reasons why farmers have relatively low awareness of the risks and impacts of soil compaction.

1.5 Measures addressing soil compaction

Measures aimed at ameliorating compacted subsoils and/or alleviating the impacts of compacted subsoils have been explored almost as long as the problem has been realized (Passioura and Leeper, 1963). Hence, many studies have examined the effectiveness of measures to ameliorate compacted subsoils and/or to alleviate the effects of compacted subsoils, including deep tillage, subsoiling, reduced tillage, crop rotation, reduced trafficking and soil amendments.

Measures addressing soil compaction may be categorized in three groups, i.e., prevention measures, amelioration measures and alleviation measures. A common opinion is that 'the best way to manage soil compaction is to prevent it from happening'. Therefore, avoiding, preventing, and precautionary strategies are preferred above amelioration and alleviation strategies, also because of the complexities and imperfections of the latter (Lebert et al., 2007; Schjønning et al., 2015). Prevention measures require a 'conservative attitude against change of the existing structure' (Alakukku et al., 2003). They aim at minimizing the traffic in fields and thereby minimize the risk of soil compaction. The effects of prevention measures are difficult to certify unless compared with reference treatments, i.e., treatments which do not take prevention measures, or treatments where the soil is compacted on purpose. Evidently, preventive measures are most useful and effective in situations where the soil is vulnerable to soil compaction but not yet (seriously) affected by soil compaction.

However, large areas in the world have already compacted soils, either through natural processes, or by human activities (Soane and Van Ouwerkerk, 1995), and thus will need amelioration and/or alleviation strategies. Remediation measures aim at reversing the states of compaction problem, by breaking up compacted soil, by deep ploughing and subsoiling. However, deep ploughing result in reversing soil horizons and burying topsoil fertility in the subsoil (Schneider et al., 2017). Moreover, the open soil condition left by subsoiling is vulnerable to re-compaction by subsequent machine traffic (Spoor, 1994).

Remediation measures should only be considered when compacted subsoils have already been formed (also because of the costs involved), and have to be carried out carefully.

Alleviation measures aim to lessen the severeness of the negative consequences of compaction. For example, additional fertilization and irrigation to alleviate moisture and nutrient deficiencies and possible yield losses caused by compaction. Additional drainage can be an effective alleviation measure in case soil compaction causes water logging. Evidently, these measures do not solve the compaction problem, but only alleviate the negative consequences of compaction. (Mujdeci et al., 2017; Ranaivoson et al., 2017). In soil science literature, alleviation measures are often labelled as 'treating the symptoms but not the root cause'. As a result, alleviation measures are often disregarded by scientists, or considered as supplementary measures.

Combined measures are common in practice, and are considered to be more efficient than single measures (Hamza and Anderson, 2005). The FAO voluntary guidelines for sustainable soil management also recommend combination of measures to prevent and mitigate soil compaction (FAO, 2017b). The need for a more coherent and integrated soil management concept was also recently emphasized by Rietra et al. (2022). A toolbox of strategies and management practices may be needed.

1.6 Knowledge gaps and research objectives

Soil compaction is a complex process, as it is influenced by a myriad of interacting factors, including soil properties, environmental conditions and soil management. Compacted soils are not easily recognized and quantified, also because there is no common, routine monitoring of soil compaction in practice. This holds especially for the subsoil. There is also discussion about the most appropriate methods, indicators and threshold values for assessing soil compaction and compacted subsoils.

Based on the literature review presented in paragraphs 1.1 to 1.6 it is evident that human-induced soil compaction is largely perceived as a problem of modern, mechanized agriculture. There is very little information and insight on the nature of soil compaction in small-holder agriculture, and on the effectiveness of possible measures aimed at ameliorating and alleviating compacted subsoils in small-holder agriculture. Of course, naturally compacted soils can be found everywhere in the world, and the problems with for example hardsetting soils in Africa, Brasil and Australia have been well described (e.g., (Daniells, 2012; Hoogmoed, 1987; Mullins et al., 1990). However, there is a lack of information on the effectiveness of measures addressing human-induced soil compaction in small-holder agriculture compared to mechanized agriculture. Is there a difference in the priority and effectiveness of measures, and if so, why? I hypothesized that the awareness and attention for soil compaction are more limited and recent in small-holder agriculture than mechanized agriculture, and that there is greater use of alleviation measures than amelioration measures in small-holder agriculture compared to mechanized agriculture.

There is also little information about spatial variations in compacted (sub)soils in practice. First, there is no routine monitoring of soil compaction in farmers' fields, because soil laboratories do not yet have appropriate and cheap methods for assessing (spatial variations of) soil compaction in the field. Second, most research related to soil compaction has been conducted in the laboratory or in field experiments. Third, simulation models may simulate spatial variations in soil compaction, based on spatial variations in soil properties derived from soil maps, and land use and axle load characteristics derived from statistics, but these are often large-scale variations beyond the field and farm scales. I hypothesized that there may be a significant within-field spatial variation in compacted subsoils in practice, and that this spatial variation may show up in spatial variations in soil functioning.

A wide range of measures have been proposed and tested to prevent or avoid soil compaction, to alleviate the impact of compacted (sub)soils, and/or to remediate compacted (sub)soils. There are also several good reviews that have summarized and synthesized the data and information of early experimental studies. However, a systematic comparison of recent results of soil compaction preventive measures, alleviation and remediation measures is lacking. Also, a comparison of the effects of aforementioned measures between small-holder farming and mechanized farming is missing. I hypothesized that soil compaction is less severe and more shallow in small-holder farming systems than in mechanized systems, and that the effects of measures will be different therefore.

No tillage (no-till) with crop residue return to the soil surface has been promoted as measure to save tillage and fuel costs, to minimize erosion and run-off, to prevent the formation of plough pans (compacted subsoil below the plough layer), and to increase soil carbon sequestration. However, no-till may decrease crop yield and increase emissions of nitrous oxide, which is a powerful greenhouse gas (Pittelkow et al., 2015a). Further, the effects of no-till in small-holder agriculture have not been elucidated yet. Examination of soil cultivation practices, including no-till, requires long-term studies, which are difficult to conduct in PhD studies. Luckily, I was involved (as MSc student) in the early stages of a long-term field experiment in China, which examined different soil cultivation practices, and again in the final stages of the field experiment (as PhD student), including the analysis of the data and write-up of the results. This long-term field experiment addressed the question which soil cultivation practice results in the highest crop yields and the least soil compaction, as derived from soil bulk density measurements.

The literature review presented in paragraphs 1.1 to 1.6 also revealed that there is a need for novel and high-precision, low-cost measures for ameliorating compacted subsoils. Deep-ploughing and subsoiling practices have been practiced for decades, but these practices have disadvantages. It is advocated that measures aimed at preventing subsoil compaction have to be prioritized, yet subsoil compaction is a continuing soil threat in mechanized agriculture. This suggests that there is a need for exploring alternative, high-precision and low-cost measures for ameliorating compacted subsoils. Evidently, developing and testing new measures is a long-term effort and may require significant investment. I developed a prototype of a measure aimed at ameliorating compacted subsoil, and tested this prototype in four field experiments in two countries in two years.

The general objective of my PhD thesis research was to increase the understanding of spatial variations in soil compaction in farmers' fields, and of the efficacy of measures aimed at the prevention, alleviation and remediation of soil compaction. The specific research objectives were:

i. to review the recent (from 2000) literature on measures aimed at the prevention, alleviation and remediation of soil compaction, and to examine possible difference between small-holder and mechanized agriculture in the effectiveness of these measures;
ii. to examine the relationships between spatial variations in subsoil compaction and spatial variations in soil properties, crop yield and nitrous oxide emissions;
iii. to examine the effects of four soil tillage practices on soil bulk density, soil carbon and nutrient sequestration and crop yield in a long-term field experiment;
iv. to develop and test a prototype measure for high-precision amelioration of compacted subsoil in small-holder agriculture and mechanized agriculture.

1.7 Outline of my thesis

In Chapter 2, I present the results of a meta-analysis of the effects of soil compaction prevention, amelioration, and alleviation measures in mechanized and small-holder agriculture, using published studies from the period 2000 to 2019/2020. The effects of the measures in terms of crop yield and soil physical properties were quantitatively analysed.

In Chapter 3, I present the results of a field study conducted in four different fields in Hoeksche Waard, the Netherlands. Within-field spatial variations in soil physical properties were quantitatively related to within-field spatial variations in crop yield and potential CO_2 and N_2O emissions from soil. Soil measurements were conducted during the first half year of the study, while crop yields were collected over a period of 3 to 4 years.

In Chapter 4, I present the results of a long-term (18 years) field experiment conducted in Luancheng, China; the effects of different tillage systems on crop yield, soil bulk density and carbon, nitrogen and phosphorus sequestration in soil were analysed. Tillage practices included traditional tillage and reduced tillage (no-till), combined with crop residue return or removal.

In Chapter 5, I present the results of four field experiments, two of which were conducted in Luancheng, China, and two in Odiliapeel, The Netherlands. A prototype of a novel, high-precision bore-hole measure for ameliorating compacted subsoil was tested, using maize and sorghum as test crops.

Chapter 6 provides the general discussion and overall synthesis of my thesis research.

2. Soil compaction prevention, amelioration and alleviation measures are effective in mechanized and smallholder agriculture: a meta-analysis

Background: *The compaction of subsoils in agriculture is a threat to soil functioning. Measures aimed at the prevention, amelioration, and/or impact alleviation of compacted subsoils have been studied for more than a century, but less in smallholder agriculture.* ***Methods****: A meta-analysis was conducted to quantitatively examine the effects of the prevention, amelioration, and impact alleviation measures in mechanized and small-holder agriculture countries, using studies published during 2000~2019/2020.* ***Results****: Mean effect sizes of crop yields were large for controlled traffic (+34%) and irrigation (+51%), modest for subsoiling, deep ploughing, and residue return (+10%), and negative for no-tillage (−6%). Mean effect sizes of soil bulk density were small (<10%), suggesting bulk density is not a sensitive 'state' indicator. Mean effect sizes of penetration resistance were relatively large, with large variations. Controlled traffic had a larger effect in small-holder farming than mechanized agriculture.* ***Conclusion****: We found no fundamental differences between mechanized and smallholder agriculture in the mean effect sizes of the prevention, amelioration, and impact alleviation measures. Measures that prevent soil compaction are commonly preferred, but amelioration and alleviation are often equally needed and effective, depending on site-specific conditions. A toolbox of soil compaction prevention, amelioration, and alleviation measures is needed, for both mechanized and smallholder agriculture.*

Based on:

Yang, P., Dong, W., Heinen, M., Qin, W., & Oenema, O. (2022). Soil Compaction Prevention, Amelioration and Alleviation Measures Are Effective in Mechanized and Smallholder Agriculture: A Meta-Analysis. Land, 11(5), 645.

2.1 Introduction

Soil compaction is defined as the 'densification of soil and the distortion of soil structure', which cause deterioration or loss of one or more soil functions (Schjonning et al., 2015; van den Akker, 2008). Compacted soils have a relatively high soil bulk density and soil strength, a low number of macro pores and a relatively high tortuosity, and thereby a low hydraulic conductivity and water infiltration rate (Batey, 2009; Nawaz et al., 2013). These phenomena increase the risks of temporal water logging, runoff and erosion (Alam et al., 2017). Compacted soils impede root elongation and development, and thereby limit soil nutrient uptake and crop development, which in turn causes yield loss (Shaheb et al., 2021; Unger and Kaspar, 1994). The altered soil aeration and wetness and the decreased root growth and crop production affect also soil biodiversity and biological activity, and thereby nutrient transformations and greenhouse gas emissions (Nawaz et al., 2013). Decreased aeration and increased wetness may predispose compacted soils also to infection of root rot diseases (Laker and Nortjé, 2020). Compacted soils are widespread and have been recognized as a global threat for modern agriculture (Caon and Vargas, 2017; Sonderegger and Pfister, 2021). Greatest concerns relate to subsoil compaction, because of the difficulty to ameliorate subsoil compaction (Alakukku et al., 2003; Techen et al., 2020).

Compacted soils are not easily recognized. This relates specially to compacted subsoils. There are various measures to assess subsoil compaction (e.g., (Batey, 2009), but there is little routine monitoring of soil compaction in practice. Yet, the concerns for soil compaction in scientific literature is steadily increasing (Fig. S2.1). This increased attention is especially related to the impacts of the increasing mechanization and wheel loads of machines in agriculture (Keller et al., 2019b). It was noted that a significant fraction of arable farmers in Germany are aware of the risk of intensive field traffic and high axle loads for subsoil compaction, but that this awareness had not yet led to adequate changes in practice (Ledermüller et al., 2021). Indeed, impacts of human-induced (sub)soil compaction seem to increase over time (Antille et al., 2019; Soane and Van Ouwerkerk, 1995; Sonderegger and Pfister, 2021).

Next to human induced soil compaction, through trafficking and ploughing (forming traffic and plough pans in the subsoil), soils may have become compacted through natural processes, e.g. during peri-glacial conditions, or as a result of the illuviation of soil colloids, cracking and swelling processes (combined with topsoil tumbling down to the subsoil when cracks are open), heavy rains, and soil trampling by animals. Soils may have a compacted subsoil also because of an abrupt textural or mineralogical change with depth, due to a different geo-genetic origin (Batey, 2009). The susceptibility of soils to compaction differs greatly. Most susceptible are soils with low soil organic matter content and a high content of silt (particles with a size of 20 to 50 µm). These soils often have a low structural stability and may be characterized as 'sealing, crusting and hardsetting' (Daniells, 2012; Laker and Nortjé, 2020).

Measures to ameliorate and/or alleviate compacted subsoils have been explored almost as long as the problem has been realized (Passioura and Leeper, 1963; Wilkins et al., 1976). Hence, many studies have examined the effectiveness of measures to ameliorate (and/or alleviate the effects of) compacted subsoils, including deep tillage, subsoiling, reduced tillage, crop rotation, reduced trafficking and using soil amendments. Results of these studies have been discussed and summarized in some excellent reviews. For example, Ungar and Kaspar (1994) reviewed studies examining root growth in compacted soils and suggested that tillage and growing deep-rooted crops in rotations will help avoid and alleviate negative impacts. Soana and Van Ouwerkerk (1994) summarized the early studies related to the nature and alleviation of soil compaction. While reviewing the literature since the early 1990s, Hamza and Anderson (2005) identified 8 practices to avoid, delay or prevent soil compaction, and suggested that combination of measures are most effective. The review of Batey (2009) largely confirmed the suggestions of Hamza and Anderson (2005) and emphasized the need for monitoring of soil compaction in practice. Nawaz et al. (2013) reviewed models simulating soil compaction and the effects of soil compaction, while Chamen et al (2015) reviewed studies examining the costs and benefits of measures aimed at ameliorating soil compaction. Schneider et al (2017) quantitatively examined the effects of deep tillage on crop yield, using a meta-analysis of data from mainly Europe and North America, and observed that deep tillage effects were highly site-specific. Shaheb et al (2021) reviewed how soil compaction affected different crop types and listed 12 management strategies to alleviate soil compaction. Most studies focused on mechanized agriculture, and paid little attention to smallholder agriculture. Of a different nature, Kodikara et al (2018) reviewed how soil compaction can be improved in civil engineering and transport.

Evidently, soil compaction is a complex and persistent phenomenon affecting the sustainability of crop production in modern agriculture in large areas of the world. The threat of subsoil compaction for crop production is thought to be most severe in mechanized agriculture with high axle loads on wet soils (Hargreaves et al., 2019; Obour and Ugarte, 2021; Schjonning et al., 2015; Techen et al., 2020). However, there are also reports on subsoil compaction in smallholder agriculture in for example China as a result of long-term soil cultivation practices, irrigation and natural conditions (e.g. (Chen et al., 2022)). It is unclear whether the effects of amelioration and alleviation measures are different between mechanized and smallholder agriculture. Machine weight is much less and ploughing depth is also less in smallholder agriculture than mechanized agriculture. We hypothesized that amelioration and alleviation measures are more effective in smallholder agriculture than in highly mechanized agriculture, because compacted soil layers are likely more shallow in smallholder agriculture, and thus easier to remediate.

We conducted a systematic review of the quantitative effects of measures aimed at preventing and ameliorating compacted subsoils or at alleviating the impacts of soil compaction on crop yield and soil physical properties, using a meta-analysis of published studies conducted in areas with smallholder farms (mainly China), and in mechanized agriculture in Europe, America, and Australia. We categorized measures in three groups (Table S2.1), largely following (Chamen et al., 2015; Hamza and Anderson, 2005): (i) measures aimed at avoiding and preventing subsoil compaction, including minimized and controlled trafficking, zero and minimum tillage (rotary tillage and shallow harrowing); (ii) measures aimed at remediating compacted subsoils, including subsoiling, deep ploughing and crop rotation; and (iii) measures aimed at alleviating the effects of compacted subsoils, including residue return, controlled irrigation, manure application. This categorization of measures also fits in the DPSIR framework (Schjonning et al., 2015).

The objectives of our study were (1) to quantitatively examine the effects of measures aimed at avoiding and ameliorating soil compaction and at alleviating the impacts of compacted subsoils on crop yield, soil bulk density, and soil penetration resistance, using results of published studies; and (2) to examine the effectiveness of measures in smallholder and mechanized agriculture. We focused on the period 2000 to 2019/2020, because of the existence of some excellent reviews covering the earlier period, and because studies on smallholder agriculture conducted before 2000 are relatively scarce.

2.2 Materials and methods

2.2.1 Data collection and screening

We searched for peer-reviewed publications investigating the effectiveness of measures to address compacted (sub)soils, using Web of Science and China Knowledge Resource Integrated Database (CNKI, for Chinese studies not published in English language). Search terms were ("soil compaction" OR "compacted soil" OR "compacted subsoil" OR "subsoil compaction") AND (yield OR biomass) AND ("density" OR "penetration" OR "soil cone index") in titles, keywords and abstracts. In Web of Science, conference proceedings and non-English publications were excluded. This search gave 719 publications published between 2000 to 2019 (until Aug 1, 2019). The search in the China Knowledge Resource Integrated

Database yielded 74 additional publications (from 2000 to Aug 2019).

The search process was followed by a screening procedure that was based on the following criteria: (1) field studies must include side by side comparisons of soil compaction prevention, remediation, and/or alleviation treatments and control (or reference) treatments; (2) for each paired comparison, treatments and reference treatments have the same location, cropping system, cropping management, and year; (3) grain yields and/or biomass yields were reported; (4) soil bulk density and/or soil penetration index data were reported; (5) the test crops were cereals, including wheat, maize, barley, oat, and sorghum; (6) location(s), year(s) and basic soil information of the experiment(s) were stated. Only studies with cereal crops as test crops were included; one reason is the importance of cereal crops in global food supply (FAO, 2021; McKevith, 2004), the other reason is that the results are likely more robust when using crops with similar root morphology and physiology (Shaheb et al., 2021). Grain yield and/or biomass yield were used as crop response indicators.

Following the aforementioned screening procedure, we obtained 378 comparisons (paired observations) of crop yields from 53 studies in 28 countries from Web of Science, and 159 comparisons of crop yields from 23 studies from CNKI. Treatment measures were recorded and grouped. The results of crop yield and soil bulk density/penetration resistance were extracted from each study, as well as characteristics related to location, experimental year(s), soil clay content and cropping system (Table S2.1). In cases where crop yield and/or soil bulk density and/or penetration results were presented in figures only, values were extracted using the GetData Graph Digitizer.

2.2.2 Categorization of the measures

The paired observations were allocated to a category of measures, i.e., prevention, remediation, or alleviation measures. There is some degree of arbitrariness in the allocation of measures. For example, the choice of crop type and crop rotation was categorized as remediation measure but could have been categorized as prevention or alleviation measures equally well. Further, alleviation measures were thought to alleviate the effects of soil compaction, but may contribute also to remediation or prevention, depending on the environmental and management conditions. Thus, irrigation, fertilization, manure application, and straw return were thought to alleviate the impacts of compacted subsoils on root growth (their limited ability to take up water and nutrients from compacted subsoils). Conventional (random) traffic was chosen as reference treatment for controlled traffic. In this case, a comparison was made between random (deliberate) trafficking and minimal or controlled trafficking, to infer the effects of controlled trafficking indirectly. Thus, random trafficking was used as reference treatment (worst-case), while minimal trafficking or controlled trafficking as the remediation treatment. The reference treatment of manure application was no manure application, while residue return was compared to no residue return. Crop rotation effects were compared to effects of mono-cropping.

Soil bulk density and soil penetration resistance results were grouped into three depth intervals: 0-20 cm (topsoil), 20-40 cm (upper subsoil), and 40-60 cm (lower subsoil). This grouping was seen as a compromise for comparing smallholder and mechanized agriculture; the depth of soil cultivation in smallholder agriculture is commonly less than 20 cm but in mechanized agriculture often a bit deeper, depending also on tillage system). Also, about 80% of the roots of most cereal crops are in the upper 40 cm and more than 95% of the roots are in the upper 60 cm of the soil (Drew and Saker, 1980; Liu et al., 2012).

Smallholder farms are mostly found in east and south Asia, Africa, and some countries of Latin America (Lowder et al., 2016), and mechanized agriculture with relatively high axle loads in North America, Oceania, Europe, and west Asia. Therefore, studies conducted in south and east Asia and Africa were considered to be small-holder farming, while studies conducted in America, Europe, Australia, and west Asia were considered to be in mechanized agriculture. For more detailed information of the database composition, see Tables S2.1 and S2.2.

2.2.3 Definitions and calculations

Our meta-analysis basically followed the same approach as the one described by Qin et al. (2015). We used the natural logarithm of the ratio of the response variable of two treatments as the effect size (Hedges et al., 1999): $\ln(R)=\ln(X_t/X_c)$, where R is the ratio, X is the response variable, and subscripts t and c refer to the specific treatment and control treatment. The response variable was either crop yield (X = Y), dry bulk density (X = BD), or penetration resistance (X = PR).

For the calculation of a grouped effect size, a linear mixed-effect model was used for which we used the R-package '*nlme'*(Pinheiro et al., 2017). Mixed-effect models are preferred to fixed-effect models for statistical testing in ecological data synthesis because their assumption of variance heterogeneity is more likely to be satisfied (Hedges et al., 1999). In our study, results of treatments addressing soil compaction were set as fixed effects and study numbers were set as random effects, to allow accounting for variances among studies. We used the equal weighting method (e.g., (Van Groenigen et al., 2014)) when comparing studies with different number of replicates. The ln(R) of the individual pairwise comparison was used as the dependent variable. The mean effect size and the 95% confidence intervals (*CIs*) of each categorical group were estimated. The significance of the effects was statistically assessed at the 0.05 confidence level. In the graphs (forest plots), the effect-size of each treatment was transformed back and converted to a percentage change in crop yield, dry bulk density, or penetration resistance relative to the control or reference treatment, i.e., data were presented as $(R-1)*100\%$. In case the value zero in such a forest plot falls outside the 95% *CI*, the given average value (effect size) is assumed to be significantly different from zero.

2.3 Results

2.3.1 Overview of the dataset

Our dataset consisted of 557 yield comparisons, 620 soil bulk density comparisons, and 592 soil penetration resistance comparisons. About half of the number of bulk density comparisons dealt with the topsoil (346), and half with the subsoil (274). More yield comparisons were from countries with predominantly small-holder farming (S-farming) (323) than from countries with predominantly mechanized agriculture (M-agriculture) (234). More yield observations were related to prevention (221) and remediation measures (205) than alleviation measures (131, Fig. 2.1a). Yield observations of prevention measures were found more in M-agriculture countries than in S-farming countries. The number of yield observations related to remediation and alleviation measures was two times larger with S-farming than M-agriculture (Fig. 2.1b, 2.1c).

2.3.2 Effects of measures on crop yields

Five out of ten measures examined had positive effects on crop yields, including prevention, remediation, and alleviation measures ($p < 0.05$, Fig. 1a). Relatively large mean effect sizes were noted for controlled traffic (+26%) and irrigation (+51%). Mean effect sizes were also significantly positive for subsoiling, deep ploughing, residue return, and crop rotation (+8% to +11%). Minimum tillage and manure application did not display significant effects, while no tillage had a negative mean effect on crop yield (−6%).

Differences between S-farming and M-agriculture in the mean effect sizes of prevention, remediation, and alleviation measures on crop yields were relatively small (Fig. 2.1b, 2.1c). The mean effect size of controlled traffic on crop yield was two time higher in M-agriculture (+38%) than in S-farming (+16%). However, the number of comparisons was much larger in M-agriculture (88) than in S-farming (21). Subsoiling was more studied in S-farming than in M-agriculture during the last 20 years and the mean effect on crop yield in S-farming was positive (+8%). Controlled irrigation and manure application were examined in S-farming but not in M-agriculture as possible measures to alleviate the effects of compacted subsoils. Evidently, controlled irrigation had a large effect size, but it is not realistic to ascribe this effect merely to the alleviation of soil compaction. Likely, crop yields in the reference treatments were limited by drought and not only by compacted subsoils.

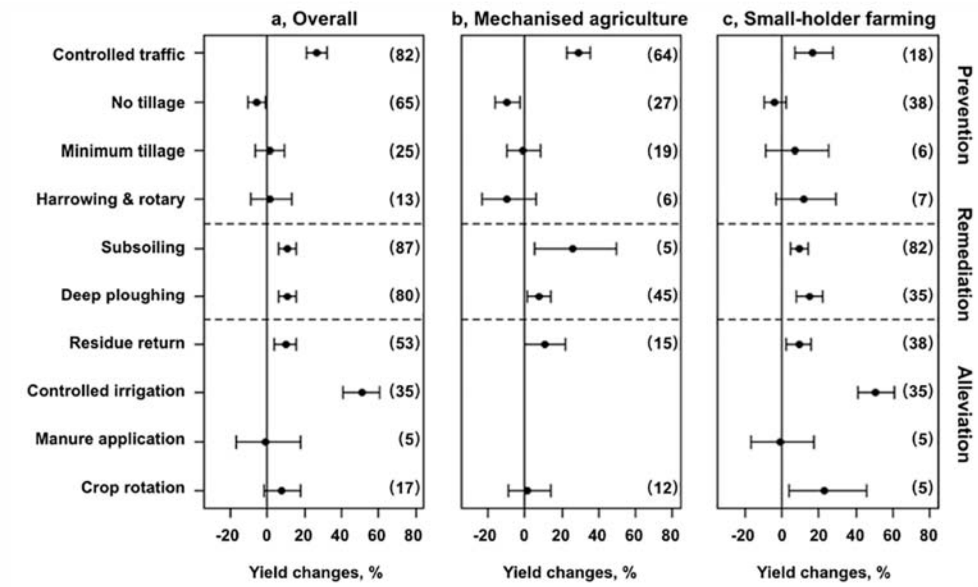


Fig. 2.1 *Relative changes in crop yield (%) in response to soil compaction prevention, remediation and alleviation measures; means of all results (a); means of results from countries with mechanized agriculture (b); means of results from countries with small-holder farming (c). Dots show means of treatments, error bars indicate 95% confidence intervals. Numbers in the parentheses indicate number of comparisons.*

2.3.3 Effects of measures on soil bulk density

The measures had a relatively small effect on the soil bulk density of the top soil and subsoil (Fig. 2.2a, 2.2d), compared to their effects on crop yields (Fig. 2.1). Relative mean changes in bulk density were in the range of 0–9%. For the subsoil, which is most critical, controlled traffic, deep ploughing, subsoiling, residue return, and crop rotation decreased soil bulk density by on average 2–9% ($p < 0.05$; Fig. 2.2d). Controlled irrigation increased bulk density in the topsoil and subsoil, while minimum tillage increased subsoil bulk density by 3% ($p < 0.05$; Fig. 2.2d).

Essentially all comparisons related to the effects of subsoiling and deep ploughing on subsoil bulk density originated from S-farming. As a consequence, no proper comparison can be made between S-farming and M-agriculture on the effects of subsoiling and deep ploughing. This holds for alleviation measures as well. Controlled trafficking decreased soil bulk density in both topsoil and subsoil, and S-farming and M-agriculture.

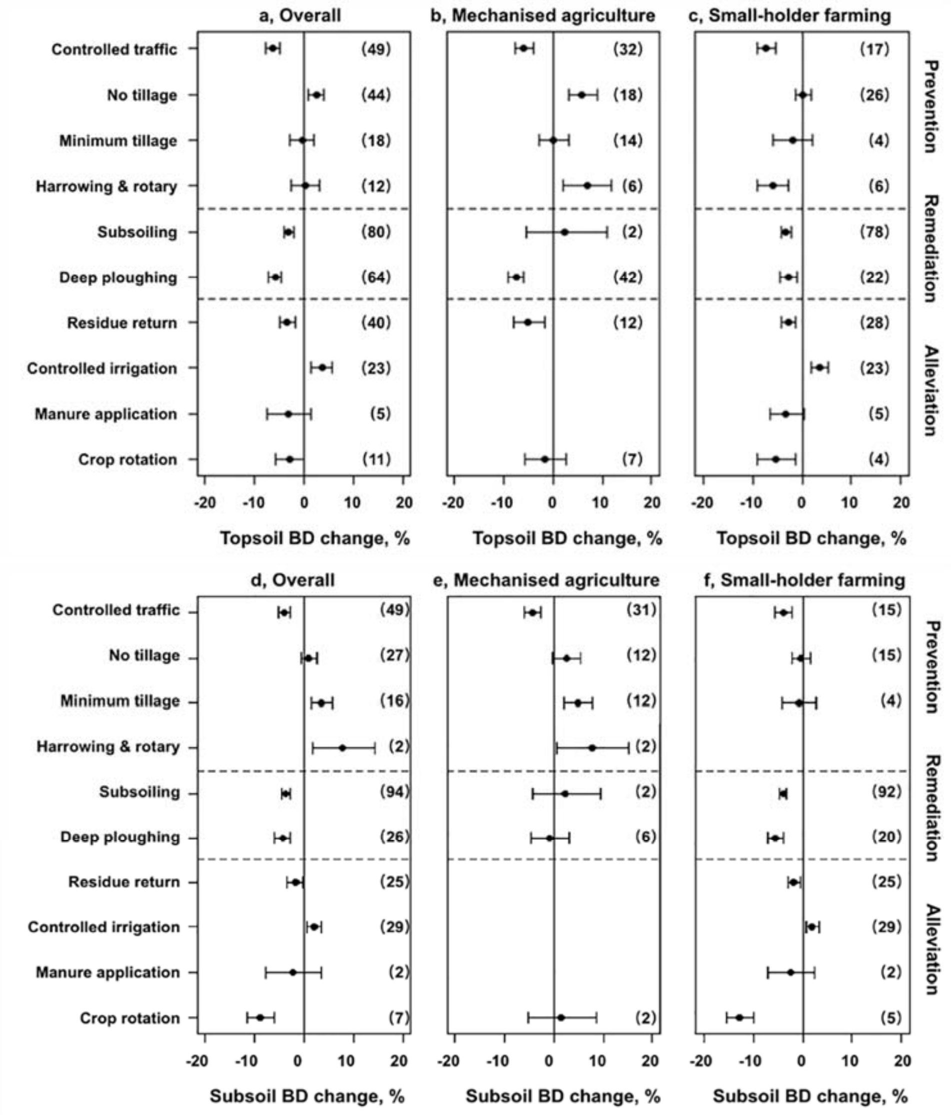


Fig. 2.2 *Relative changes in soil bulk density (BD) in response to soil compaction prevention, remediation and alleviation measures for the topsoil (a, b, c) and for the subsoil (d, e, f); means of all results (a and d); means of results from M-agriculture (b and e); means of results from S-farming (c and f). Dots show means of treatments, error bars indicate 95% confidence intervals. Numbers in the parentheses indicate number of comparisons.*

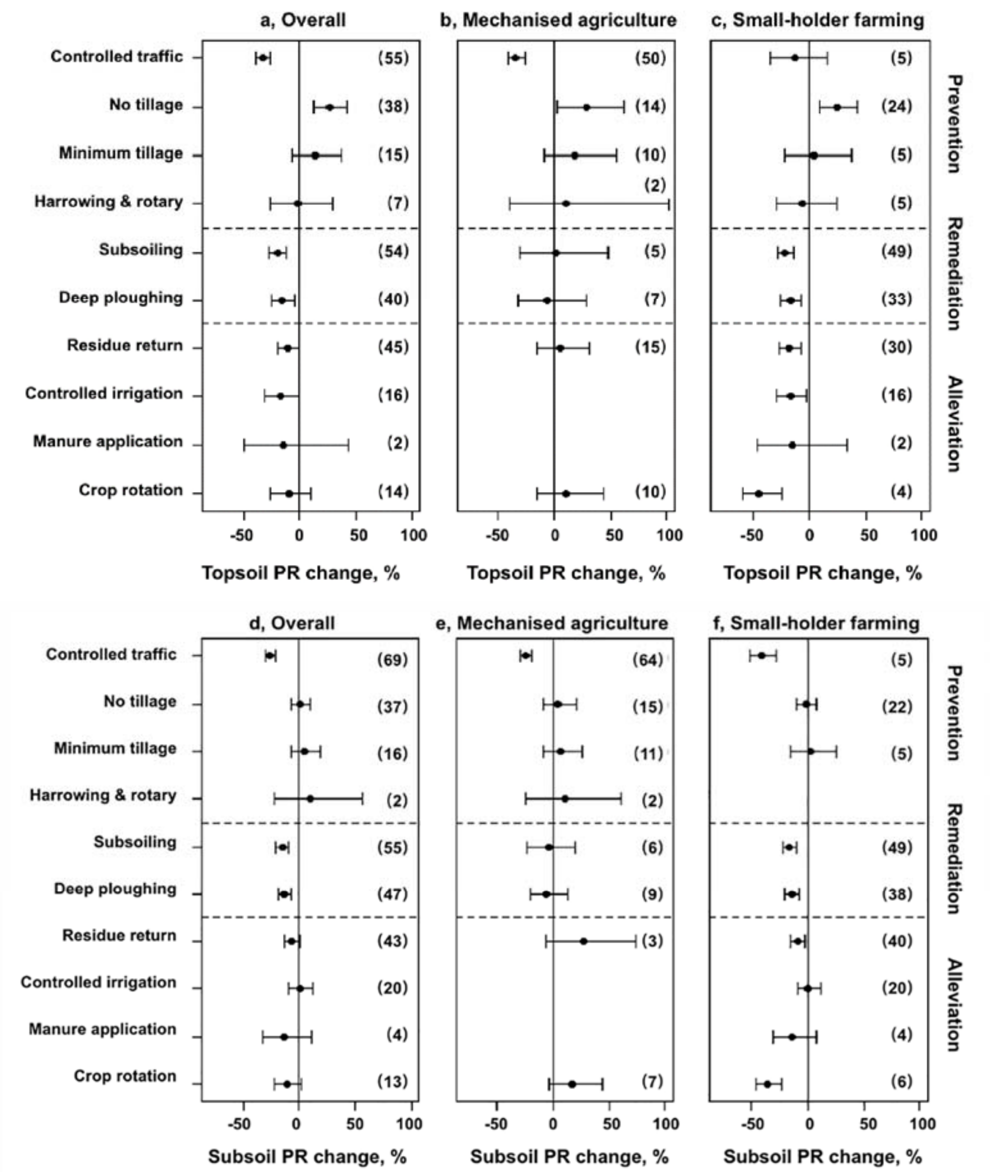


Fig. 2.3 *Relative changes in soil penetration resistance (PR) in response to soil compaction prevention, remediation and alleviation measures for the topsoil (a, b, c) and for the subsoil (d, e, f); means of all results (a and d); means of results from M-agriculture (b and e); means of results from S-farming (c and f). Dots show means of treatments, error bars indicate 95% confidence intervals. Numbers in the parentheses indicate number of comparisons.*

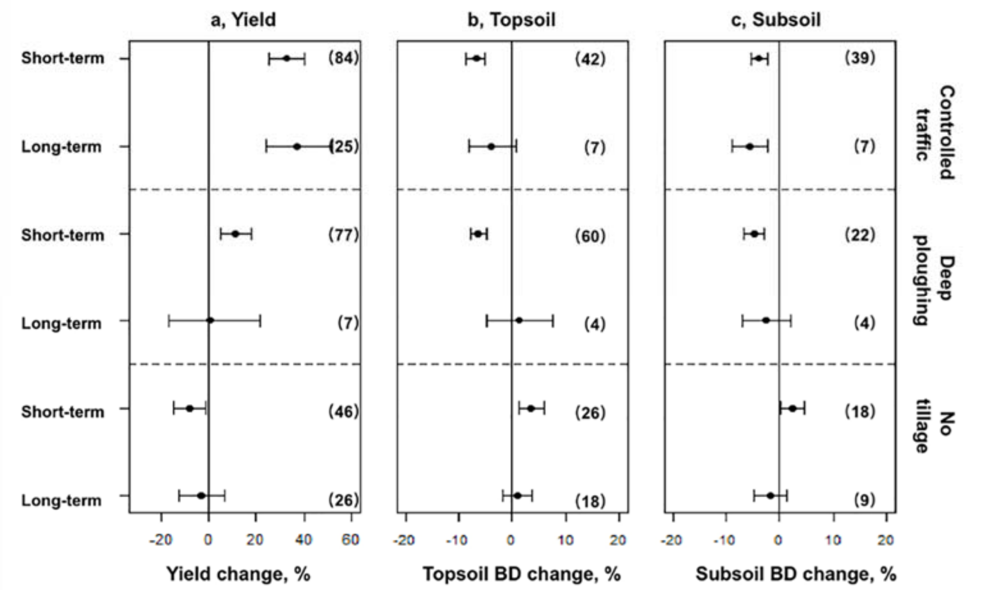


Fig. 2.4 *Relative changes in crop yield (a) and soil bulk density (BD; for top soil, b; and subsoil, c) in response to various soil compaction prevention, remediation and alleviation measures; means and standard deviations of results from short-term (<4 years), and long-term (⩾4 years) field experiments.*

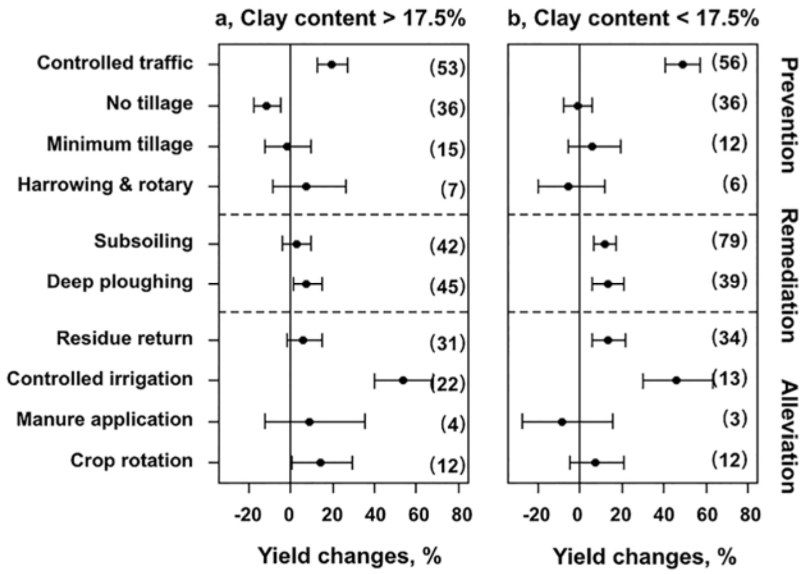


Fig. 2.5 *Relative changes in crop yield (%) in response to soil compaction prevention, remediation and alleviation measures; means of results from clay soil (clay content ≥17.5%) (a); means of results from sandy soil (clay content <17.5%) (b). Dots show means of treatments, error bars indicate 95% confidence intervals. Numbers in the parentheses indicate number of comparisons.*

2.3.4 Effects of measures on soil penetration resistance

Soil penetration resistance responded to the measures in a similar way as bulk density, but the relative changes were larger (Fig. 2.3a, 2.3d). Controlled traffic treatments had on average 33% lower penetration resistance in topsoils and 26% lower resistance in subsoils than the reference treatments. Subsoiling and deep ploughing decreased penetration resistance by 13% to 20% ($p < 0.05$, Fig. 2.3d). No tillage increased penetration resistance in the topsoil but not in the subsoil.

Observations on subsoiling and deep ploughing originated mainly from S-farming countries, where these measures decreased penetration resistance. Residue return decreased penetration resistance in both topsoil and subsoil in S-farming. The number of comparisons for residue return was too low in M-agriculture to make firm statements. Irrigation slightly decreased penetration resistance in the topsoil but not in the subsoil in S-farming.

2.3.5 Effects of experimental duration

More than 80% of the comparisons dealt with short-term experiments (1~3 years; Table S2.1). Tillage treatments (deep ploughing, subsoiling, no tillage, minimum tillage) accounted for almost half (47%) of the long-term experiments (≥4 years), followed by controlled traffic (23%). For controlled traffic, the relative effect size for crop yield and for subsoil bulk density tended to increase over time (Fig. 2.4a). For crop yield, the effect size was 33% in short-term and 37% in long-term experiments, while subsoil bulk density was 4% lower in short-term and 6% lower in long-term experiments compared to the reference treatments ($p< 0.05$; Fig. 2.4b, 2.4c). For deep ploughing, the relative effect size for crop yield and bulk density decreased over time. In short-term (1~3 yrs) experiments, mean effect sizes were statistically significant on crop yields and bulk density ($p < 0.05$), but not in long-term (≥4 yrs) experiments. Similar results were found for no tillage (Fig. 2.4).

2.3.6 Effects of soil texture

Soil texture (silt and clay contents) and soil organic matter content affect the susceptibility of soils to compaction and also likely influence the effect sizes of measures. A clay content of 17.5% is commonly used as a threshold value in soil compaction evaluation. Soils with <17.5% clay are considered to be more susceptible to compaction than soils with ≥17.5% clay. Thus, we compared the effect sizes of measures for soils with <17.5% clay with soils having ≥17.5% clay. Yield effects were on average similar for the two textural classes (Fig. 2.5). However, light-textured soils (<17.5% clay) showed greater responses to prevention and amelioration measures than heavy-textured soils (≥17.5% clay). This was most notable for controlled traffic. Effect sizes for yield differed by more than a factor two (+49% vs. +19%;

p < 0.05), for subsoiling (+12% vs. 3%), and deep ploughing (13% vs. 8%; p < 0.05).

2.4 Discussion

2.4.1 Understanding the cause-effect relationships

The cause–effect relationships of soil compaction and its mitigation measures can be analyzed and understood through the 'driving forces, pressures, state, impact, responses' (DPSIR) framework (Schjonning et al., 2015) . In agriculture, the driving forces often stem from the economic incentives to produce more and to lower costs, especially in affluent countries (Alakukku et al., 2003; Keller et al., 2019b). This leads to more intensive soil cultivation and the use of larger and heavier machines, which exerts literally pressure on the soil. This pressure may lead to a densification of the (sub)soil, i.e., compacted (sub)soils, with impacts on water infiltration, root and crop growth, microbiological processes, and gaseous emissions, e.g., (Batey, 2009). The response of farmers and land managers may be directed towards avoiding or preventing soil compaction, i.e., addressing the driving forces and pressures, or they may focus on the amelioration of compacted soils, i.e., addressing the state, or at alleviating the impacts of compacted soils, or both (Fig. 2.6). Thus, the three categories of measures distinguished in our meta-analysis (Table S2.2; Fig. 2.1) address different aspects of the cause–effect chain of soil compaction.

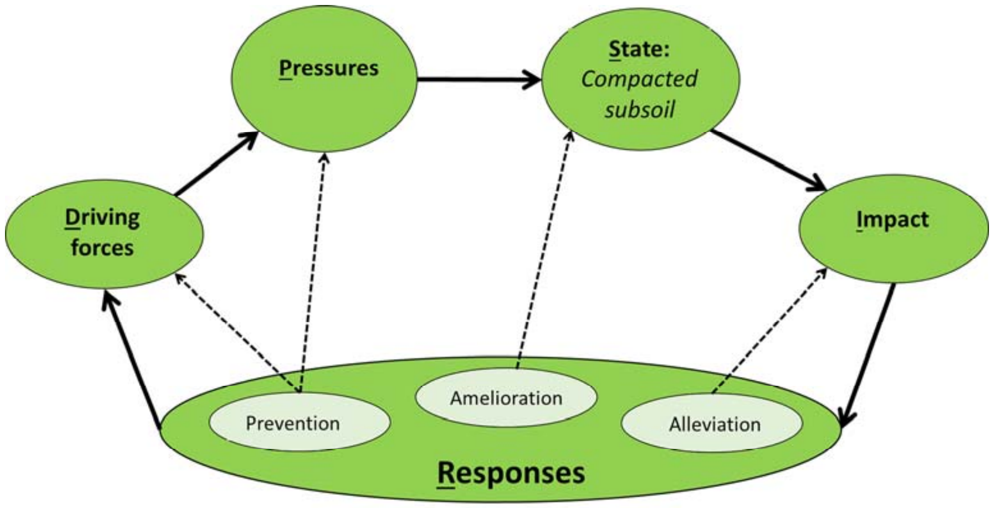


Fig. 2.6 *The Driver-Pressure-State-Impact-Response (DPSIR) concept with focus on soil compaction. The response measures indicate which part of the DPSIR chain is being addressed by the measures.*

Avoiding, preventing and precautionary strategies are preferred above amelioration and alleviation strategies, also because of the complexities and imperfections of the latter (Lebert et al., 2007; Schjonning et al., 2015). However, large areas in the world have naturally compacted subsoils (e.g., (Daniells, 2012; Laker and Nortjé, 2020)), or have been compacted by human activities in the past (Soane and Van Ouwerkerk, 1995), and thus will need amelioration and alleviation strategies. Moreover, the susceptibility of soils to densification and the farming and environmental conditions greatly differ across the world, suggesting that region- and farm-specific strategies will be needed, and thus a toolbox of options and strategies. Our meta-analysis contributes to this toolbox by examining quantitatively the effects of both prevention, amelioration, and alleviation measures.

Depending on the strategy, different indicators may be used for evaluating the effectiveness of the strategy. Lebert et al (2007) discussed indicators for precautions against soil compaction (pressure indicators) and for the impairment of subsoil structure through compaction (state indicators). For the first, they proposed the 'pre-compression stress' and 'loading ratio', which can be calculated for different soils, but need soil type specific calibration (2007). For assessing the impairment of subsoil structure, they proposed three indicators, i.e., air capacity (>5% air filled porosity at a water suction of pF 1.8), saturated water conductivity (< 10 cm day^{-1}), and a visual classification of the soil morphology (combination of a 'spade diagnosis' and measurements of the effective bulk density and packing density). The second suggested indicator (saturated water conductivity) basically is an impact indicator (and not a state indicator). Soil bulk density was not recommended as indicator for identification of 'harmful' soil compaction, because 'there is no critical threshold and classification scheme' according to the authors (Lebert et al., 2007). However, for the related 'packing density' (bulk density corrected for clay content) indicator, there are criteria (Jones et al., 2003). Håkansson and Lipiec (2000) reviewed the usefulness of the relative soil bulk density, or the degree of compactness, which was defined as the dry bulk density in percent of a reference dry bulk density of the same soil obtained by a standardized, long-term uni-axial compression test at a stress of 200 kPa. Evidently, the measurements of the state of soil compaction are labor-intensive and thus costly, especially when considering spatial within-field variations (Lipiec and Usowicz, 2018; Yang et al., 2022). As a result, routine monitoring of the state of soil compaction in farmers' fields is not common practice. Indeed, it appears costly and there is debate about appropriate indicators and their interpretation. We observed that soil bulk density and penetration resistance are most commonly used as indicators for assessing the state of soil compaction in field experiments to test measures aimed at preventing, ameliorating, and/or alleviating soil compaction. However, bulk density is not a sensitive indicator (e.g., relative changes in soil bulk density following the implementation of measures are relatively small; Fig. 2.2), while penetration resistance is very sensitive to variations and changes in soil moisture content. Based on uni-axial tests, Panayiotopoulos et al (2003) showed that for a compression stress up to 300 kPa the dry bulk density changed up to 5~15%. This suggests that extreme changes in dry bulk density are not likely to occur. Further, measurements of penetration resistance should be performed at pressure heads of about −100 cm. It is, however, unlikely that this was the case in all studies. This may explain why a large variability in penetration resistance was found in the reviewed studies.

Impact indicators relate to the changes in soil ecosystem functioning following a change in the densification of the soil and associated changes in pore size distributions, tortuosity and soil structure. Possible impact indicators are crop yield, hydraulic conductivity, run-off and ponding, and emissions of CO_2, CH_4 and N_2O (Batey, 2009; Tullberg et al., 2018). There are no critical thresholds and classification schemes for assessing changes in soil functions, apart perhaps from hydraulic conductivity (Lebert et al., 2007). Yet, comparisons can be made between situations without and with compacted (sub)soils as in our meta-analysis. Crop yield is probably the most powerful indicator in farmers' practice, because of its influence on farm income, although part of a yield penalty may be nullified through alleviation measures, including irrigation and fertilization.

In conclusion, the DPSIR framework is useful for analyzing and understanding the cause-effect relationship of soil compaction, but further work is needed to derive a proper set of indicators and threshold values.

2.4.2. Impacts of measures in low-tech and high countries

The mean effect of controlled traffic on crop yield was 38% (range 32–45%) in mechanized agriculture (M-agriculture) and 16% (range 6–27%) in small-holder farming (S-farming). The wide range of yield effects is roughly in the same range as reported by Antille et al. in a review of 20 studies for various crops (Antille et al., 2019). The yield of crops was 0–98% higher when grown in the absence of field traffic compared to the yield of crops grown under typical traffic intensities. Controlled traffic was introduced in commercial-scale farming in the 1990s, initially in Australia and subsequently in Europe and northern America (Rietra et al., 2022; Tullberg et al., 2007). The net economic benefit of controlled traffic increases with farm area. Conversely, the yield effect of controlled traffic needs to be relatively large to make controlled traffic economically attractive in small farms (Antille et al., 2019; Chamen et al., 2015). It is therefore no surprise that the number of experimental studies was much larger in M-agriculture than S-farming (Fig. 2.1b, 2.1c). Interestingly, the mean yield effect of controlled traffic was on average a factor of two smaller in S-farming than in M-agriculture, which may indeed reflect differences in axel loads between S-farming and M-agriculture.

Zero-tillage minimizes the traffic of soil-cultivating tractors and was therefore considered to be a preventive measure for soil compaction, but it does not necessarily control the traffic of other (e.g., harvesting) machines in the field. There is a lot of interest in zero-tillage and minimum tillage (e.g., (Rietra et al., 2022), as it saves labor and fuel cost, minimizes erosion (especially when combined with surface mulching), and contributes to enhanced soil carbon sequestration. However, it increases N_2O emissions and decreases crop yield. The latter is in agreement with our findings (Fig. 2.1). Further, it tends to increase the soil bulk density and penetration resistance of the topsoil (Fig. 2.2, 2.3). The no-till (or reduced-till) compacted topsoils limit root penetration and plant growth (Troccoli et al., 2015), while crop residues remaining on the soil surface may increase the incidence of viruses and plant pathogens (Pittelkow et al., 2015a), and lower the soil temperature (Ali et al., 2018; Graven and Carter, 1991). Our study indicates that current zero-tillage and minimum tillage practices are much less effective as a preventive measure for soil compaction than controlled traffic. However, there is a need for more soil physical and soil structural measurements (including bulk density) of the subsoil in no-till systems to confirm our findings.

Deep ploughing and subsoiling increased crop yields by on average 10% and 9%, respectively, though with relatively large uncertainty bars (Fig. 2.1a). These mean effects were derived mainly from studies conducted in S-farming and reported between 2000 and 2019/2020. Schneider et al. (2017) reported rather similar mean positive effects of deep tillage on crop yield (6%), based on a meta-analysis of 45 studies (67 field experiments) that were mainly conducted in Europe and North America between 1918 and 2014 (only three studies were reported after 2000, namely one from North America, one from Argentina, and one from China). They noted that the popularity of deep tillage decreased from the 1970s. Peralta et al. Peralta et al. (2021) also found positive mean effects of subsoiling on the yield of maize (+6%) and soybean (+26%) in no-till systems in Argentina, using a meta-analysis of 32 field studies. Our study indicates that positive effects of deep tillage on crop yields also hold for smallholder farming, notably China, for both deep tillage and subsoiling. Schneider et al. (Schneider et al., 2017) found that the mean effect size of deep tillage on crop yield depended on the silt content of the topsoil, the density of the subsoil, and drought, but not on the deep tillage method (subsoiling vs. deep ploughing and deep mixing) and tillage depths. The strong interference by drought agrees with our observation that irrigation alleviates the effects of compacted subsoils and greatly increases crop yield (Fig. 2.1). The effect of deep ploughing on crop yield decreased over time (Fig. 2.4). A similar trend was observed in the meta-analysis studies of Schneider et al. (2017) and Peralta et al. (2021).

The decreasing effect of deep tillage over time is likely the result of re-compaction (Peralta et al., 2021; Schneider et al., 2017). Our analyses indicate that deep tillage decreased soil bulk density (Fig. 2.2) and penetration resistance (Fig. 3) of the topsoil and subsoil. Similar decreases were noted for the topsoil by Peralta et al. (2021), but neither Peralta et al. (2021) nor Schneider et al. (2017) reported changes in soil bulk density and/or penetration resistance for the subsoil in response to deep tillage.

Alleviation measures mainly aim to lessen the negative impacts of compacted subsoils on root and crop growth. Roots elongate less in compacted and dry soils due to a combination of mechanical impedance and water stress (Bengough et al., 2011) , and thereby have less access to soil moisture and nutrients. Irrigation thus greatly alleviates the negative impacts of compacted subsoils on crop yield. The mean effect size of irrigation on crop yield was 50% (Fig. 2.1). However, irrigation increased soil bulk density in the topsoil and subsoil (Fig. 2.2). These results are based on observations in S-farming countries only, i.e., mainly China. Crop residue return or surface mulching also had a positive on crop yield, likely because of its effect on soil water preservation (Qin et al., 2015). Crop residue return decreased soil bulk density (Fig. 2.2), possibly as a result of enhanced soil carbon sequestration (Rietra et al., 2022). Only a few studies explicitly examined the effects of manure application on alleviating impacts of compacted subsoils on crop yield. No significant effects on crop yields were found, but manure application in S-farming tended to decrease soil bulk density, possibly through enhancing soil organic carbon contents (Mujdeci et al., 2017; Ranaivoson et al., 2017). In summary, alleviation measures 'treat the symptoms but not the root cause', yet some of these measures can be highly effective, also in cases where amelioration measures were not much effective.

2.4.3 Managing soil compaction

A common opinion is that 'the best way to manage soil compaction is to prevent it from happening'. The popularity of controlled traffic and reduced or no till practices reflects this opinion. The increasing wheel loads and weight of agricultural machinery in practice in especially Europe and North America during the last 60 years do not reflect this opinion. The increase in machinery weight has resulted in an increase in subsoil compaction, which may have contributed to crop yield stagnation and to an increase in the incidence of flooding in Europe (Keller et al., 2019b). The cascade of possible impacts from soil compaction beyond field and farm scales (e.g., increased risk of flooding, runoff, and erosion) could be seen as driver for actions by policy (Horn et al., 1995a; Thorsøe et al., 2019). However, soil compaction is not subject to a coherent set of rules in, for example, the European Union (EU), and is also not mentioned in the recent EU soil strategy for 2030 (Commission, 2021).

Thus, farmers depend on the insights and guidelines of their own and their advisors when it comes to handling soil compaction, while there are essentially no monitoring data concerning farmers' fields.

There is less risk of soil compaction by machines in small-holder farming in China, for example, than in the mechanized agriculture of Europe, North America, and Oceania. There is also no governmental policy aimed at preventing soil compaction in China. However, the intensive cultivation practices and irrigation, and the silty texture of the dominant loss soils in north China are conducive to soil compaction, and there is therefore a continuous search for soil conservation practices that decrease the risk of soil compaction and improve soil structure (Chen and Shaw, 2022; Zhou et al., 2019). A combination of tillage practices in sequence appears to be the best strategy (Fen et al., 2021; He et al., 2019; Tian et al., 2016). This holds for no-till as well. However, it has to be combined with subsoiling once in a few years, as also discussed for the no-till agriculture in Argentina by Peralta et al. (2021). The need for combining tillage practices in China also follows indirectly from the increasing interest in subsoiling during the last two decades (e.g., Fig. 2.1 (Chen et al., 2022)).

The FAO voluntary guidelines for sustainable soil management do provide technical and policy recommendations to prevent and mitigate soil compaction (FAO, 2017a). Though qualitative and without threshold values, these guidelines are interesting because they address not only the machines and vehicles in the field, but also the importance of crop type and crop rotation, soil organic matter content, soil macrofauna, and microbial and fungal activities. Amelioration measures are not explicitly mentioned, apart from the recommendation to also grow crops with strong tap roots able to penetrate and break up compacted soils. Next to soil compaction, the FAO guidelines also present recommendations to prevent and mitigate nine other soil threats (FAO, 2017a). The need for a more coherent and integrated soil management concept was also recently emphasized by Rietra et al. (2022). They presented a roadmap for developing high-yielding, soil-improving, and environmentally sound cropping systems. This roadmap involves an iterative selection and optimization of site and farm specific crop husbandry and soil management practices, including the selection of machines that minimize soil compaction.

Evidently, preventing soil compaction from happening is too simple a strategy to address soil compaction. Rather, a toolbox of strategies and management practices is needed, which can be used to develop and implement site-specific management measures. Our study provides evidence that both prevention, amelioration, and alleviation measures have value, depending on the site-specific conditions. These measures provide net economic benefits for farms in most cases, through increases in crop yields and resource use efficiency

(Chamen et al., 2015; Hallett et al., 2012). The selection of the most appropriate measures will likely improve, and the effectiveness of these measures will likely increase, when more data become available at the farm level, related to the state and impact of soil compaction, through routine monitoring.

2.4.4 Limitations of our study

We focused on the recent literature (2000–2019/2020), because there are some excellent papers that reviewed and analyzed the older literature, e.g., (Mariotti et al., 2020; Schneider et al., 2017), and not many studies have been conducted in small-holder agriculture before 2000. We examined literature from both mechanized agriculture and small-holder farming to make comparisons between these two types of agricultural systems, based on the literature from 2000–2019/20. We note that the literature from S-farming countries from before 2000 has not been analyzed in a systematic manner yet, apart from the studies by Hoogmoed et al. (1992), and the reviews by Laker and Nortjé (2020), and Peralta et al. (2021).

Further, we note that the machine weight is rapidly increasing over time (Keller et al., 2017), not only in M-agriculture countries, but also in some S-farming countries. Hence, the rough categorization in S-farming and M-agriculture countries may not be the best way to examine differences between mechanized and smallholder agriculture, although this comparison provided new insights, e.g., related to the type of measures applied in the two types of agriculture.

Crop types may respond differently to compacted soils and thereby also to prevention, amelioration, and alleviation measures, because of differences in root morphology and physiology (Ball et al., 2005; Bengough et al., 2011). We selected cereals as test crops because these were mostly used and have a more or less uniform response. Thereby, we excluded 183 studies with non-cereal test crops out of the 719 available studies (25%).

Further, we excluded studies that combined various measures, e.g., controlled traffic combined with no tillage, controlled traffic combined with deep tillage, tillage combined with residue management levels, and irrigation combined with subsoiling. The exclusion of these studies does not mean that these studies are less relevant. Instead, it requires another study to infer useful conclusions from these combined-measures studies.

2.5 Conclusions

Our meta-analysis included 77 studies from 28 countries (32 studies from 16 countries for mechanized agriculture (M-agriculture), and 45 studies from 12 countries for small-holder farming (S-farming)) all related to the effectiveness of soil compaction prevention, amelioration, and alleviation measures. These studies were published between 2000 and 2019/2020 and thus are relatively recent. Prevention measures were mostly studied in M-agriculture, while remediation and alleviation measures were mostly studied in S-farming.

Soil compaction prevention, through controlled traffic, had a positive effect on crop yield in both M-agriculture (+38%) and S-farming (+16%) countries, and led to a lower soil bulk density in topsoil and subsoil (−4% to −6%), and to a lower soil penetration resistance (−26% to −33%). These results confirm earlier estimates for M-agriculture countries but now show that controlled traffic also holds promise for S-farming. However, it is not clear whether controlled traffic is economically profitable in S-farming. Soil compaction prevention through no-till had negative effect on crop yield, while bulk density was increased, in both M-agriculture and S-farming.

Soil compaction amelioration through deep tillage (including subsoiling) had positive effects on crop yields (+9% to +10%), while soil bulk density was decreased by about 3%. These results confirm earlier observations for M-agriculture, but we show that these observations are also valid for S-farming. The relatively large number of studies related to deep tillage in S-farming suggest that subsoil compaction is increasingly seen as a constraint to crop production in the countries with S-farming.

Irrigation was an effective alleviation measure for subsoil compaction, though only reported for S-farming. The large mean effect size for crop yield (+51%) reflects that compacted soils impede root elongation and thereby enhance the impacts of drought, though the effect of irrigation likely relates not only to alleviation of drought related to compacted subsoils. Crop residue mulching and manure application had a small effect on alleviating compacted subsoils.

Soil penetration resistance and bulk density were mostly used as state indicators. Effect sizes of measures on soil bulk density were small (<10%), indicating that bulk density is not a sensitive indicator for assessing the effects of measures. Effect sizes of crop yield as an impact indicator were relatively large, but variable because of interfering factors (climate, soil texture).

A toolbox of soil compaction prevention, amelioration, and alleviation measures is also needed because the cause of soil compaction and the responses of measures are site-specific. Our meta-analysis indicates that such a toolbox is needed for M-agriculture and S-farming.

Acknowledgements:
The present study was carried out in the EU project SoilCare ("Soil care for profitable and sustainable crop production in Europe"), EU grant agreement 677407; and National Key Research and Development Program of China (2021YFD190100202).

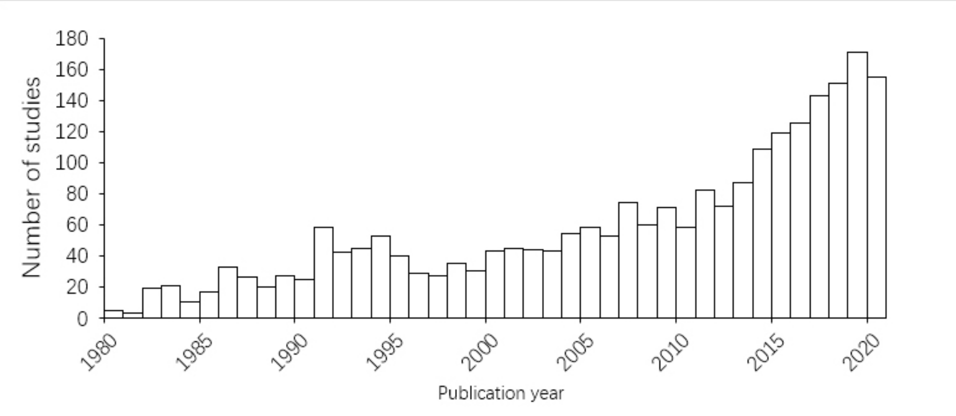


Fig. S2.1 *Number of papers published per year, studying the relationships between soil compaction and crop yield. Searched by "soil compaction * yield" in Web of Science, from 1980 to 2021*

Table S2.1 *Studies included in this meta-analysis*

ID	References	Country	clay content	Duration
1	Abu-Hamdeh NH, 2003	Jordan	0.41	2
2	Afzalinia S, 2014	Iran	0.41	2
3	Ahmad N, 2009	Pakistan	0.2	1
4	Andersen MN, 2013	Denmark	0.07	1
5	Bhattacharyya R, 2015	India	0.1	4
6	Blanco-Canqui H, 2007	USA	0.153	2
7	Bogunovic, I.2018.	Croatia	0.236	14
8	Cai Lijun. 2014	China	0.08	1
9	Chen H, 2013	China	0.037	9
10	Chen H, 2015	China	0.037	3
11	Chen L, 2014	China	0.1465	1

12	Chen Yi. 2013	China	0.28	1
13	Chen Yi. 2014	China	0.28	1
14	Diaz-Zorita M, 2000	Argentina	0.145	1
15	Edward WILCZEWSKI	Poland	0.06	3
16	Feng Fuxue. 2010	China	0.1	2
17	Filipovic D, 2006	Croatia	0.228	1
18	Galambosova, J.2017.	Slovakia	0.19	1
19	Ge Shuangyang. 2017	China	0.3555	1
20	Giacomeli et al. 2017	Brazil	0.265	1
21	Gregory AS, 2007	UK	0.14	2
22	Guo H, 2014	China	0.19	1
23	Hamza MA, 2008	Australia	0.035	1
24	Hao Yaxing. 2015	China	0.37	1
25	Hassan FU, 2007	Pakistan	0.12	1
26	He Mingrong. 2004	China	0.18	2
27	He, Y. B.2017.	China	0.553	1
28	Huang Yingbo. 2016	China	0.3287	3
29	Iijima M, 2005	Japan	0.302	2
30	Ishaq M, 2003	Pakistan	0.24	4
31	Ivan A. Dozier	US	0.1	2
32	Kahlon, M. S.2017.	India	0.09	1
33	Kong Xiangbin. 2012	China	0.15	1
34	Kustermann B, 2013	Germany	0.222	11
35	Lars J. Munkholm	Canada	0.16	2
36	Li Bangfa. 2016	China	0.12	1
37	Liu Ming. 2012	China	0.182	1
38	Lopez-Garrido R, 2014	Spain	0.25	4
39	Malecka I, 2015	Poland	0.12	10
40	Martinez I, 2014	Chile	0.148	2
41	Maughan MW, 2009	USA	0.35	1
42	Moraru PI, 2012	Romania	0.439	3
43	Mu XY, 2016	China	0.12	3
44	Mueller L, 2009	Canada	0.15	10
45	Mueller L, 2009	Germany	0.255	10
46	Munkholm LJ, 2005	Denmark	0.132	6
47	Munkholm LJ, 2008	Denmark	0.09	2

48	Nevens F, 2003	Belgium	0.123	1
49	Pang Xu. 2013	China	0.14	3
50	Peigne, J.2018.	France	0.15	10
51	Peng Chenglin. 2019	China	0.126	1
52	Qiao Yunfa. 2018	China	0.1741	1
53	Raus L, 2016	Romania	0.41	4
54	Reintam E, 2008	Estonia	0.15	1
55	Reintam E, 2009	Estonia	0.13	1
56	Salem HM, 2015	Spain	0.21	1
57	Schjonning P, 2016	Denmark	0.34	4
58	Seehusen T, 2014	Norway	0.39	1
59	Singh VK, 2006	India	0.16	2
60	Singh, K.2019	India	0.08	1
61	Singh, S. P.2017.	Bangladesh, India, Nepal	0.22	1
62	Sun, H.2018.	China	0.1275	17
63	T. GŁA¿B	Poland	0.25	8
64	T. Seehusen.2019	Norway	0.095	1
65	Tolon-Becerra A, 2011	Spain	0.2167	1
66	Tracy BF, 2008	USA	0.35	4
67	Tran Ba Linh	Vietnam	0.66	10
68	Wang Chanjun. 2011	China	0.15	1
69	Wang Y, 2005	Canada	0.617	2
70	Wang, S. B.2019.	China	0.1819	1
71	Xu Huan.2017	China	0.0473	1
72	Yan Yongxin, 2010	China	0.0755	5
73	Yan Yufei. 2010	China	0.34	1
74	Zhang Fengjie. 2016	China	0.1686	1
75	Zhang Yayun. 2017	China	0.09	1
76	Zhu W, 2016	China	0.1304	1

Table S2.2 *Soil compaction prevention, remediation and alleviation measures; their mechanisms and limitations.*

Measures		Description/explanation/ definition	Main limitations
Prevention	CTF traffic	avoid irreversible plastic deformation of the soil, through minimizing the ground contact area of wheels	the high entry cost; long intervals between machinery replacements
	No/min til	Avoids negative effects of conventional tillage; High saturated and unsaturated hydraulic conductivity; High soil moisture and water use efficiency;	Weed control cost, chemical herbicides use; Elevated moisture levels in the topsoil may promote fungal diseases; Yield decreases (especially in the short term)
	Harrow tillage	A harrow whose cutting edges are a row of concave metal discs, which may be scalloped, set at an oblique angle.	Only the soil within the vicinity of the disc harrow action (0–20 cm) was influenced
	Rotary tillage	The loosening and inverting of soil to a depth of 20–25 cm with a rotating tines or blades.	only works on topsoil compaction; brings residues to sowing depth, thereby affecting crop emergence rate;
Remediation	subsoiling	to shatter dense subsurface soil horizons without turning the soil and burying fertile topsoil in the subsoil	power and energy consuming; effects last shortly; Increases the vulnerability to re-compaction
	Deep tillage	To break up high density to a depth of 40–50 cm or more	Power and energy consuming; Turns soil profiles; Reduces earthworm diversity and numbers; Soil structure deterioration in the long-term
	Rotation	biological drilling	Limited by types of crops;
Alleviation	Residue returning	Increase soil organic matter, binding soil mineral particles; reducing aggregate wettability; increasing soil mechanical strength	lead to excessive soil moisture and water logging in flood; lower soil temperatures in cooler climates;
	Irrigation	Alleviate water deficiency;	Negative effects on crop yields and soil bulk density are also detected
	Manure application	Provide nutrient, and alleviate yield loss due to water and nutrient deficiency.	Possible air pollution due to N_2O emission and water pollution due to leaching

3. Within-field spatial variations in subsoil bulk density related to crop yield and potential CO_2 and N_2O emissions

Subsoil compaction is an increasing problem in modern agriculture, but is not easily recognized in practice, also because of possible within-field spatial variations. This paper addresses the question of how within-field spatial variations in soil bulk density and other soil characteristics relate to within-field spatial variations in crop yield and potential CO_2 and N_2O emissions from soil. Four fields (5 to 20 ha each) were selected at the suggestion of crop farmers, and sampled using a random soil sampling design (100 samples per field). Undisturbed soil samples were taken at depth of 5-10, 30-35, and 50-55 cm and soil bulk density and potential CO2 and N_2O emissions measured under controlled conditions. At each sampling point, also top soil (0-20 cm) samples were taken for determination of pH, texture, SOM, and (micro)nutrients, and soil penetration resistance measurements and visual assessments of soil structure were made. Wheat yields were recorded with harvesters equipped with GPS and yield recorders.

Mean soil bulk density in the sub-soil (30-35 cm) ranged between fields from 1.36±0.08 to 1.60±0.11 g cm^{-3}. Mean wheat yields ranged between fields and years from 7.6±0.6 and 11.3±2.4 Mg ha^{-1}. Semi-variogram analyses showed that crop yields and soil properties were mostly spatially dependent; nugget-to-sill ratios were < 25% with ranges of 137 to 773 m. The ratio of CO_2 emissions to N_2O emissions was negatively related to soil bulk density, especially following N application.

In conclusion, within-field spatial variations in subsoil bulk density were successfully related to spatial variations in crop yield and potential CO_2 and N_2O emissions. The ratio of CO_2 emissions to N_2O emissions had a much greater response to spatial variations in soil bulk density than wheat yield. Our study suggests that N_2O emission factors may depend on (sub)soil bulk density.

Based on:

Yang, P., Reijneveld, A., Lerink, P., Qin, W., & Oenema, O. (2022). Within-field spatial variations in subsoil bulk density related to crop yield and potential CO_2 and N_2O emissions. Catena, 213, 106156.

3.1 Introduction

Subsoil compaction is an increasing problem in modern agriculture, but is not easily recognized in practice. Reports indicate that > 68 million ha of agricultural land in the world have compacted subsoils. More than half of this area is in Europe (Hamza and Anderson, 2005; Wahlström et al., 2021). Soil compaction is commonly defined as the densification and distortion of soil by which total porosity and air-filled porosity are reduced and one or more soil functions are deteriorated (Banerjee et al., 2019; Huber et al., 2008; Schjonning et al., 2015). By reducing air permeability and limiting water infiltration, soil compaction may restrict root growth and nutrient uptake, which consequently affect soil functioning, including crop productivity, infiltration and storage of water and the decomposition of organic matter and transformation of nutrients (Keller et al., 2013). Compaction may be induced by natural factors, like alternate freezing-thawing and trampling of animals, as well as by human influences, i.e., through soil cultivation and heavy machinery (Keller et al., 2019b).

Indicators for soil compaction include increases over time of soil bulk density, Relative Normalized Density (RND, defined as the actual dry bulk density divided by a critical or threshold bulk density), penetration resistance, and decreases over time of macro-porosity and infiltration capacity (Chamen et al., 2015; Shah et al., 2017b; Stolte et al., 2015; van den Akker and Hoogland, 2011). Not all these indicators can be measured easily in the field and they do not equally account for changes in the volume distribution of voids and their connectivity. As a result, relationships between indicators for subsoil compaction and soil functioning are not always straightforward (Horn et al., 1995b; Keller et al., 2017).

Most of our understanding of subsoil compaction and its effects has been obtained in controlled condition experiments, also because there is no routine monitoring in farmers' fields of soil compaction and/or soil bulk density. Also, measurements of within field spatial variations in sub-soil bulk density have been carried out mostly in experimental fields (e.g., (Awal et al., 2019; Barik et al., 2014; Usowicz and Lipiec, 2017). Very few studies have examined spatial variations in subsoil bulk density in farmers' fields and have tried to relate these variations to spatial variations in crop yield and soil (microbiological) processes. The overall aim of our study was to increase the understanding of within-field spatial variations in (sub)soil bulk density in farmers' fields, and its relationships with spatial variations in crop yield and potential CO_2 and N_2O emissions (the latter as proxies for microbial activity). We hypothesized that (i) subsoil compaction is partly 'hidden' in spatial within-field variations in farmers' fields, and (ii) within-field spatial variations in subsoil compaction contribute to spatial variations in crop yield and soil microbial activity.

3.2 Materials and methods

3.2.1 Study area

The study was conducted in Hoeksche Waard, one of the islands (300 km^2) in the delta of southwest Netherlands (Fig. 3.1). It has a temperate maritime climate with cool summers and moderate winters. Annual mean precipitation is 850 mm, rather evenly distributed over the year. Hoeksche Waard is mainly used for arable farming (Ecorys, 2007); crop rotations include potato, sugar beet, winter wheat and horticultural crops (Crittenden et al., 2015; Steingrover et al., 2010). Most farms are family farms, but contractors may do part of the field work (e.g., manure application and potato, wheat and sugar beet harvesting). Farm size ranges between 50 to 500 ha, depending in part on crop rotations. Fields are flat (slope <0.1%) and are drained by surrounding ditches and subsurface drains at depth of 0.8 to 1.2 m with 10 to 30 m wide spacings. Many fields have become larger over time through closing ditches and re-parceling.

Soils have developed in marine deposits and have light clay to sandy clay texture in the upper half meter and loamy sand below. They are classified as Calcaric Fluvisols (WRB, 2006). Mean groundwater level in winter is 45~60 cm and in summer 140~170 cm below soil surface.

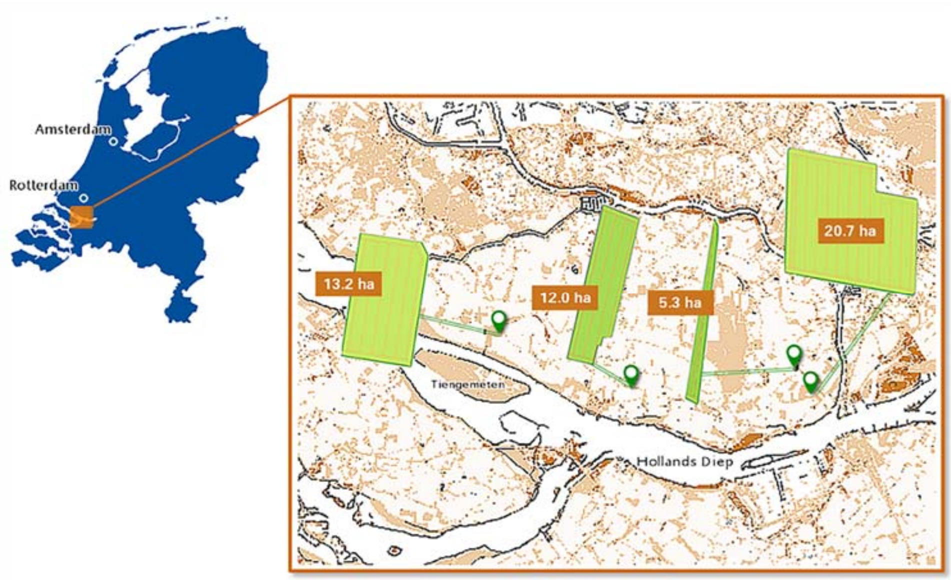


Fig. 3.1 *Locations of the study area in the delta of south-west Netherlands. The inset shows the location of the four study fields.*

3.2.2 Soil sampling design

Four fields with different shape and size (from 5.3 to 20.7 ha) and from four different farms were chosen (Fig. 3.1), following discussions with farmers of the foundation H-Wodka, which aims at enhancing the vitality of the rural agricultural community, nature and landscape in Hoeksche Waard through innovation. The farmers have concerns about the sustainability of current agricultural practices; they consider that spatial variations in soil compaction and soil fertility are possible barriers for increasing crop yield, but currently have no data and information to underpin these concerns. Farmers either had a 1:4 crop rotation (potatoes - winter wheat/vegetables/onions – sugar beet – winter wheat with cover crops) or a 1:3 crop rotation (potatoes – sugar beet/onions/vegetables – winter wheat). We selected fields in winter wheat; these fields had potatoes or sugar beet as pre-crops. Farmers ploughed the top 25 cm of soil with a moldboard plough, prior to seeding winter wheat in rows with a row distance of 12.5 cm. They aim at 250-300 wheat plants per m^2, 550 to 600 ears per m^2, and a grain yield of ≥10 Mg ha^{-1} yr^{-1}.

A total of 100 soil-sampling points were randomly selected within each field, using ArcGis software, in the spring of 2016. A total of 100 samples per field is generally considered to be an appropriate number for obtaining adequate insight in the spatial pattern of soil properties in agricultural fields of modest areas (Kerry and Oliver, 2007; Lawrence et al., 2020). At each sampling point, two sampling approaches were implemented. First, 5 samples of the topsoil (0-20 cm depth) were taken by augers within a circle with a radius of 5 m and then bulked and mixed (total weight about 2 kg) in plastic bags and transported within 5 hours to a temperature conditioned room (4°C) until further analysis. Secondly, undisturbed soil samples were taken at each point by stainless steel rings of exactly 100 cm^3, at three different depths. Soil sampling depths were based on observations in soil pits and discussions with farmers, and were uniform for all fields: 5-10 cm (plough layer), 30-35 cm (underneath the plough layer), and 50-55 cm, using the same auger hole. The undisturbed soil samples in stainless steel rings with plastic caps on the top and bottom were transported in wooden boxes within 5 hours to a temperature conditioned room (4° C) and stored until further analysis. Each field was sampled within two to three consecutive days; all fields were sampled within a three-weeks period.

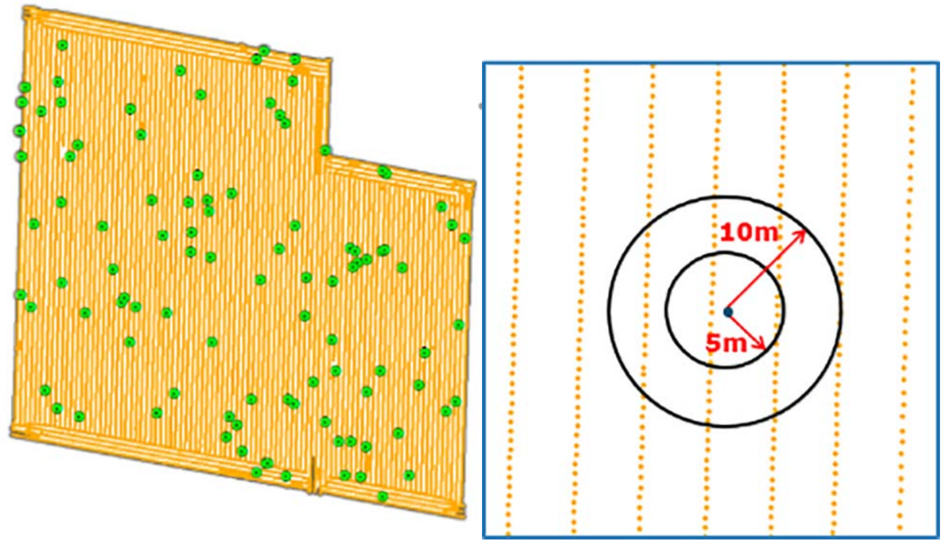


Fig. 3.2 *Soil sampling points (green dots) in one of the fields (left panel), and a sketch of the recording of grain yield (yellow dots) with the harvester in a field (right-hand side figure). The circles indicate how grain yield recordings were allocated to a soil sampling point, in two ways, using a radius of 5 or 10 m around the soil sampling point (see text). Harvested yield recordings (yellow points) were implemented by real-time measurements and GPS equipped on the harvest machine.*

Penetration resistance was measured with a hand-held penetrograph (Stiboka penetrograph, Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands). Within a circle with a radius of 5 m around each sampling point, the penetrometer was pushed into the soil manually at a fixed speed of about 30 mm s^{-1} (ASABE, 2006) at three randomly selected places. The area of the conical point was $1cm^2$ and the measuring depth was 0 to 80 cm. Results for depth of 5-10 cm, 30-35 cm, and 50-55 cm depth were averaged per sampling point. Penetrometer measurements of a single field were carried out within one day.

Soil structure assessments of the top soil (0-5 cm) were made on the basis of visual observations (Mueller et al., 2009; Pulido Moncada et al., 2014). Soil aggregation (structureless, weak structure, moderate structure, and strong structure), aggregate shape (granular, blocky, prismatic & columnar, and platy), and aggregate size (fine (<0.5 mm), medium (0.5 - 2 mm), coarse (2.0 - 5 mm), and very coarse (>5 mm)), were recorded at each sampling point.

3.2.3 Soil analyses

Samples from the topsoil (disturbed) were dried at 40 °C overnight. Near Infra-Red Spectroscopy was used for analyzing soil texture, soil organic matter, N-total, S-total and

$CaCO_3$ according NEN-EN-ISO 17184 (ISO17184, 2014). The NIRS method was calibrated and validated on the basis of thousands of different soil samples from different areas in Europe (Reijneveld et al., 2021). The $CaCl_2$ extraction method (0.01 M; 1:10 (w/v) combined with Inductivity Coupled Plasma (ICP), Inductivity Coupled Plasma-Massa Spectrometry (ICP-MS) and segmented flow analyses (for NH_{4+} and NO_3^-) were used to measure plant-available (micro) nutrients (N, S, P, K, Mg, Na, Si, Fe, Zn, Mn, Cu, Co, B, Mo, Se), following NEN 5704 (1996) and Van Erp (1998). The pH of the $CaCl_2$ extract was measured with a combination electrode and a potentiometer. These analyses were conducted by Eurofins Agro (https://www.eurofins.com/agro).

Undisturbed soil samples in stainless steel rings were measured for soil bulk density and potential emissions of N_2O and CO_2 in temperature (16 °C) and humidity (60%) conditioned rooms at Wageningen University. These emission determinations are meant to reflect the intrinsic characteristics of the soil samples at uniform environmental conditions (and not the actual or in-situ emissions in the field), and are therefore termed 'potential emissions. Following pre-incubation at 16 °C for 1 day, the uncapped soil samples in stainless steel rings were put in 1 L PVC jars with screw lid with rubber septa for 60 minutes. Changes in potential N_2O and CO_2 concentrations in the headspace of the jars were measured via the photo-acoustic infrared gas analyser Innova 1312 (LumaSense Technologies A/S, Ballerup, Denmark). After these flux measurements, 12 ml $NaNO_3$ solution (2.4 g N L^{-1}) was gently sprayed on top of each soil sample, to simulate a common N fertilization of 150 kg per ha. One day (24 hours), four and six days after fertilization, soil samples were put in jars again, and changes in N_2O and CO_2 concentrations in the headspace were measured; these are reported as 'induced N_2O and CO_2 emissions.

N_2O emissions were calculated using the following equation:

$$F_{N_2O} = \frac{(C-O)}{VAT}\frac{28}{22.4} \qquad (1)$$

Here, F is the emission rate (mg N_2O-N m^{-2} day^{-1}); C is the measured N_2O concentration (mg N_2O-N m^{-3}); O is the initial N_2O concentration (mg N_2O-N m^{-3}); V is the volume of the headspace (jar volume minus soil cylinder volume, L); A is the cross-sectional area of soil sample (m^2); T is the closing time (h); 22.4 is the number of moles per volume of air (1 liter = 1/22.4 mol); 28 is the mol weight of N in N_2O (1 mol N_2O-N = 28 g N).

Similarly, CO_2 emissions were calculated using the following equation:

$$F_{C_2O} = \frac{(C-O)}{VAT}\frac{12}{22.4} \qquad (2)$$

The parameters are the same as in equation (1), with 12 the mol weight of C (1 mol CO_2 = 12 g C).

After the potential CO_2 and (induced) N_2O emission measurements, soil samples in the rings were saturated with water, weighted, dried for 24 hours at 105 °C and then again weighted to determine total pore volume and dry bulk density. The relative normalized density (RND) was estimated as the ratio of measured bulk density and a threshold value of bulk density (van den Akker and Hoogland, 2011). For sand and loamy soils (clay content < 16.7 %), this threshold value is 1.6 g cm^{-3}; for soils with clay content > 16.7 %, the threshold value is (1.75–0.009*clay content).

3.2.4 Yield recordings and calculation

Crop yields were recorded automatically during the harvesting of the wheat. The width of the harvesters was 5 m and the distance between yield recordings on-the-go were about 2 m. Recorded crop yields within circles around sampling points were averaged and then allocated to these soil sampling points. We used circles with a radius of 5 m and 10 m, to assess the uncertainty in allocation (Fig. 3.2). This allocation allowed us to relate spatial variations in crop yields to spatial variations in soil characteristics.

3.2.5 Data analysis

Spatial distributions of crop yield and soil properties were displayed by ArcGis 10.2.1, using Inverse Distance Weighted (IDW) interpolation (Lloyd, 2005).

Spatial dependence and spatial distribution coefficients of crop yield and soil properties were displayed by GS+ software, using the semi-variogram method (Gamma Design Software, GS+9, 2008). The semi-variogram is the basic geostatistical tool for measuring spatial autocorrelation of a regionalized variable (Hohn, 1998). This method describes the structure and randomness of spatial variables, and quantitatively describes the spatial distributions.

First, all data per field were tested for normal distribution; data of most variables were not obedient to normal distributions (analyzed by the *shapiro.test* function of R studio (Kassambara, 2019). The data of these variables were then log-natural transformed. Exponential, gaussian, spherical, and linear models were selected for the semi-variograms. Three parameters were distinguished: the nugget variance (Co; i.e., the y-intercept of the model; the sill (Co+C; i.e., the model asymptote; and the range (A; i.e., the distance over which spatial dependence is apparent (Robertson, 2008). The nugget ratio (Co/(Co+C)) indicates the spatial dependence, i.e., a variable is considered spatially dependent if the nugget ratio is <25% (Cambardella et al., 1994) .

We established regression models on the basis of our hypotheses, using crop yields and potential N_2O and CO_2 emissions as response variables and a range of soil variables as explanatory variables. Statistical analyses were carried out by R software (RCoreTeam, 2013). We used multiple linear regression models (function *lm()* in R) (James et al., 2013). Only explanatory indicators (regressors) that were sufficiently uncorrelated ($r < 0.70$) have been included in the selection process to avoid the problem of collinearity (Ott and Longnecker, 2010). In case of high correlations, one of the variables was selected for inclusion in the selection process and the other was rejected. To identify the best parameter combinations, the percentage of variance accounted for (R^2_{adj}; i.e., adjusted for the number of parameters), the value of Mallows' Cp (Ott and Longnecker, 2010), and the p value of the parameter estimates were evaluated. The selected models were based on the marginal increase of R^2_{adj} with increasing number of variables, a low Cp, and the significance of the parameters ($p < 0.05$).

3.3 Results and discussion

3.3.1 Mean soil characteristics of the four fields

Soil bulk density varied within and between fields and tended to increase with soil depth (Fig. 3.3). Field A had the lowest bulk density, at all three depths, and fields B and D the highest bulk density, notably in the subsoil. Field B had a mean bulk density of 1.60±0.11 g cm^{-3} at 30-35 cm and field D had a mean bulk density of 1.58±0.10 g cm^{-3} at 30-35 cm. The mean RND at a depth of 30-35 cm ranged from 0.86±0.05 for field A to 1.03±0.07 for field B, to 0.95±0.06 for field C and to 1.00±0.07 for field D (Tables S3.1, S3.2), indicating that mean subsoil bulk density in fields B and D is at a level where soil functioning may be impeded (van den Akker and Hoogland, 2011). This relates especially to root growth and drainage (Alaoui et al., 2011; Berisso et al., 2012; Czyz, 2004; Matthieu et al., 2011).

The increasing soil bulk density with soil depth is likely the result of both a decreasing clay content (and increasing sand content) with depth and of the use of heavy machinery (for harvesting potatoes and sugar beet, and manure application). The manure applicators and crop harvesters have become heavier over time and do contribute to the densification of the subsoil (Keller et al., 2019b; Schjonning et al., 2015; van den Akker et al., 2013). A modelling study suggested that 43% of the agricultural land in the Netherlands has a compacted subsoil (Brus and Van Den Akker, 2018a), but confirmation by measurements is lacking. Especially clay soils are vulnerable to compaction when wet (Horn et al., 1995b).

Soil penetration resistance increased with soil depth, notably below a depth of about 30 cm (Figs. S3.1, S3.2). Spatial variations in penetration resistance readings were relatively large (c.v. ranged from 23 to 76%, Table S3.1). Comparisons between fields are confounded by differences in soil moisture conditions between fields due to the time differences in measurements (days to weeks).

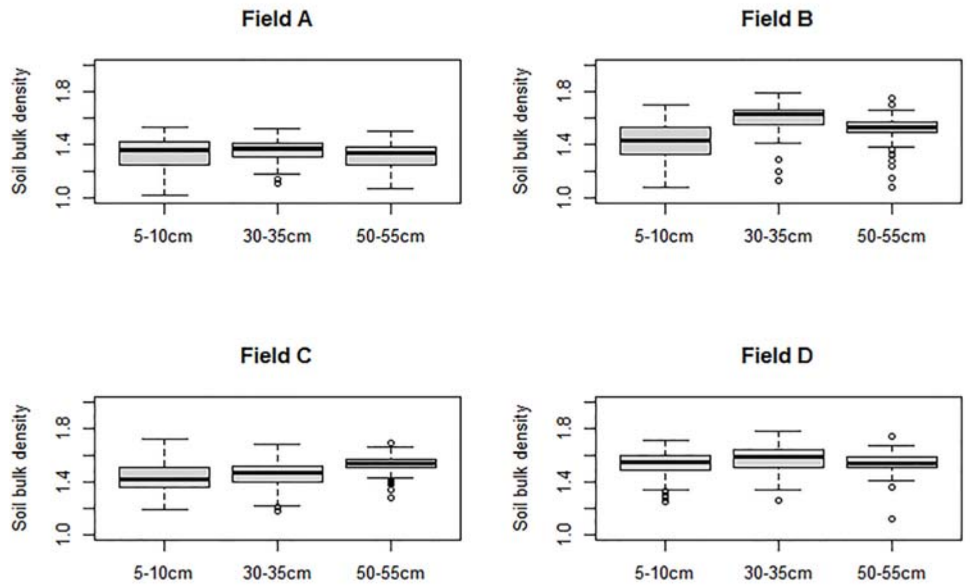


Fig. 3.3 *Box plots of soil bulk density measurements in the four fields (A, B, C, D) at three different depths. Boxes indicate the upper (75%) and lower quartiles (25%) and the whiskers indicate the 5 and 95 percentiles. The line in the boxes indicate the median values. The unit of bulk density is g cm*$^{-3}$.

Mean soil respiration (CO_2 emissions) tended to decrease with depth in all fields. The c.v. of the mean potential CO_2 emission was about three times larger in field A than in the other fields; this is probably related to the relatively large variation in SOM content of field A (Table S3.1). Mean potential N_2O emissions tended to increase with depth. The ratio of potential CO_2 emissions to potential N_2O emissions also decreased with depth; this was most notable in field A (Table S3.1). Incidental negative N_2O emissions (apparent N_2O reduction) occurred in samples from all four fields. Coefficients of variations were larger for the potential N_2O and CO_2 emissions than for bulk density, clay and SOM contents.

Average wheat yield ranged from 7.6±0.6 to 11.3±0.5 Mg ha^{-1} in field A during 2015 to 2019, and from 11.0±0.3 to 11.3±2.4 Mg ha^{-1} in field B (Table S3.1). In field C, average wheat yield was 9.5±0.9 and 9.7±1.3 Mg ha^{-1} in 2017 and 2019, respectively. Coefficients of variations were relatively small for wheat yield in all three fields and years. There were no spatial explicit yield recordings for other crops, and no spatial explicit wheat yield data were available for field D.

3.3.2 Spatial variations in soil characteristics and crop yields

Within-field spatial variations were observed visually in the maps of subsoil bulk density (Fig. 3.4), the wheat yield maps (Fig. S3.3), and in the maps of potential CO_2 and N_2O emissions of the top soil (Fig. S3.4). These spatial patterns seemed to be related partly to the spatial patterns in soil structure of the top soil (Fig. S3.5) and in the clay content (not shown).

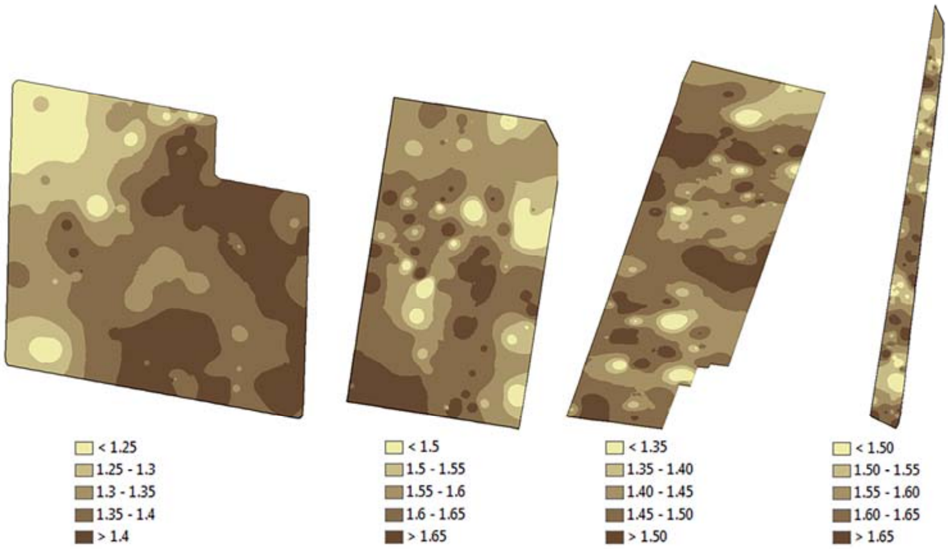


Fig. 3.4 *Maps depicting the spatial variations of soil bulk density (g cm^{-3}) at a depth of 30–35 cm of the four fields. Note that the scaling differs between fields.*

Results of semi-variogram analyses of soil variables and wheat yields of the four fields are presented in Table 3.1. Exponential models gave the best fit for most variables (17 out of 50 soil characteristics examined for the four fields), followed by a spherical model (15), a gaussian model (14) and a linear model (4). The correlation coefficients (R^2) of the models used were relatively high (range 0.52 to 0.97) for field A, modest (range 0.07-0.97) for field B, low to modest for field C (range 0.01-0.88) and low for field D (range 0.01-0.26). The poor fit of the models for field D may be related to the unusual narrow shape of this field, despite the fact that this field had a relatively small area (Fig. 3.1). We used a fixed number of 100 sampling points for all four fields, despite their different sizes and shapes, because we had no prior information about within-field spatial variations. However, this number should not be considered as the optimum number of sampling points for all fields.

Table 3.1 *Semi-variogram coefficients of soil properties and cereal yields of four fields. Note that emissions of CO_2 and N_2O are potential CO_2 and N_2O emissions (see text).*

Fields	Variables†)	Model	Nugget, C_0 $(Unit)^2$	Sill, (C_0+C) $(Unit)^2$	Range, A (m)	Nugget ratio, $C_0/(C_0+C)$	R^2
A	SOM content	Gaussian	0.01	0.13	572	0.11	0.97
	Clay content	Gaussian	0.02	0.20	662	0.11	0.96
	Soil BD (0-5cm)	Exponential	<0.01	0.01	60	<0.01	0.52
	Soil BD (30-35cm)	Gaussian	<0.01	0.01	356	0.45	0.78
	Soil BD (50-55cm)	Spherical	<0.01	0.01	558	0.25	0.85
	N_2O emission (5-10cm)	Gaussian	0.13	0.64	85	0.20	0.81
	N_2O emission (30-35cm)	Exponential	0.02	0.41	108	0.05	0.73
	N_2O emission (50-55cm)	Spherical	0.12	0.41	187	0.28	0.83
	CO_2 emission (5-10cm)	Exponential	<0.01	0.72	224	<0.01	0.92
	CO_2 emission (30-35cm)	Exponential	<0.01	0.77	229	<0.01	0.93
	CO_2 emission (50-55cm)	Spherical	0.12	0.75	175	0.15	0.86
	Wheat yield (2015)	Spherical	<0.01	0.01	418	0.21	0.85
	Wheat yield (2018)	Exponential	<0.01	0.01	576	0.19	0.91
B	SOM content	Exponential	0.01	0.05	1089	0.23	0.69
	Clay content	Gaussian	3.17	13.23	415	0.24	0.94
	Soil BD (0-5cm)	Exponential	<0.01	0.02	13	0.07	0.07
	Soil BD (30-35cm)	Gaussian	<0.01	0.01	22	0.03	0.50
	Soil BD (50-55cm)	Exponential	<0.01	0.01	192	0.50	0.43
	N_2O emission (5-10cm)	Spherical	0.01	0.13	56	0.08	0.42
	N_2O emission (30-35cm)	Linear	0.07	0.07	241	1.00	0.08
	N_2O emission (50-55cm)	Spherical	<0.01	0.07	22	0.05	0.32
	CO_2 emission (5-10cm)	Exponential	0.01	0.11	37	0.11	0.43
	CO_2 emission (30-35cm)	Spherical	0.01	0.27	36	0.02	0.42
	CO_2 emission (50-55cm)	Exponential	0.05	0.18	177	0.30	0.90
	Wheat yield (2015)	Gaussian	<0.01	0.03	165	0.01	0.97
	Wheat yield (2019)	Exponential	<0.01	0.00	137	0.13	0.55
C	SOM content	Gaussian	<0.01	0.01	5	0.20	<0.01
	Clay content	Spherical	<0.01	0.05	24	0.08	0.05
	Soil BD (0-5cm)	Gaussian	<0.01	0.01	24	0.18	0.43
	Soil BD (30-35cm)	Gaussian	<0.01	0.01	19	0.17	0.05
	Soil BD (50-55cm)	Gaussian	<0.01	<0.01	16	0.15	0.01
	N_2O emission (5-10cm)	Exponential	0.01	0.10	29	0.15	0.07
	N_2O emission (30-35cm)	Spherical	0.01	0.15	17	0.04	<0.01
	N_2O emission (50-55cm)	Spherical	0.03	0.02	31	0.12	0.18
	CO_2 emission (5-10cm)	Linear	0.06	0.06	342	1.00	0.09
	CO_2 emission (30-35cm)	Exponential	0.01	0.09	1	0.08	<0.01
	CO_2 emission (50-55cm)	Spherical	<0.01	0.02	21	0.04	0.03
	Wheat yield (2017)	Exponential	<0.01	0.01	268	0.12	0.88
	Wheat yield (2019)	Exponential	0.01	0.03	773	0.19	0.82
D	SOM content	Exponential	<0.01	0.02	35	0.15	0.11
	Clay content	linear	0.01	0.01	449	1.00	0.10
	Soil BD (0-5cm)	Spherical	0.02	0.05	691	0.34	0.26
	Soil BD (30-35cm)	Spherical	<0.01	0.01	32	0.06	0.14
	Soil BD (50-55cm)	Gaussian	<0.01	<0.01	6	0.22	<0.01
	N_2O emission (5-10cm)	Exponential	0.40	2.82	31	0.14	0.07
	N_2O emission (30-35cm)	Gaussian	0.04	0.23	6	0.19	<0.01
	N_2O emission (50-55cm)	Gaussian	0.03	0.15	20	0.19	0.01
	CO_2 emission (5-10cm)	Spherical	0.02	0.10	72	0.20	0.18
	CO_2 emission (30-35cm)	linear	0.07	0.07	449	1.00	0.02
	CO_2 emission (50-55cm)	Spherical	<0.01	0.02	25	0.11	0.03

†) SOM content, g/kg; clay content, %; soil (BD) bulk density, g/cm^3; N_2O and CO_2 emissions, mg/m^2/d; wheat yield, Mg/ha

The nugget effect was small in most cases (Table 3.1), indicating that the small-scale variance was relatively small and that the sampling design was adequate to measure the spatial variability of the studied variables (Bogunovic et al., 2017). The nugget-to-sill ratio (Co/(Co+C)) was low (<25%) for most variables, indicating that the variations in these variables were spatially dependent (Cambardella et al., 1994). Variations in soil bulk density were spatially strongly dependent at all three depths, apart from field A (at depth of 30-35 and 50-55 cm) and field B (at depth of 50-55 cm). Within-field variations in clay and SOM contents of the topsoil were also spatially strongly dependent, apart from the clay content in field D. Within-field variations in wheat yield in fields A, B and C were also spatially depended, for all years (Table 3.1). The same applies to the potential CO_2 and N_2O emissions during the incubation of soil samples; the within-field variations in the emissions of CO_2 and N_2O were spatially depended at all three depth, apart from three cases (two for CO_2 and one for N_2O emissions).

The range (A in Table 3.1) of the spatially dependent variance tended to be smaller for soil bulk density than for clay and SOM contents. It was mostly <50 m for soil bulk density in fields B, D and C. The semi-variograms of potential CO_2 and N_2O emissions also showed a relatively small range. No attempts were made to estimate values in points at which no samples have been taken through ordinary kriging (Lipiec and Usowicz, 2018), as small ranges make spatially explicit management complicated. Wheat yields had a relatively strong spatial dependency with a range of 137 to 773 m, suggesting that some of this variation may be addressed possibly by precision management.

Within-field variations in crop yield may be caused by spatial variations in soil water and soil nutrient delivery to the crop, spatial variations in the incidence of weeds, pest and diseases, and to spatial variations in soil and crop management practices (e.g. planting density, fertilization, crop protection) (Basso et al., 2019; Maestrini and Basso, 2018; Taylor et al., 2003). Extractable nutrients (N, P, K, Mg, Cu, Zn, Se) were spatially dependent in a number of cases, with ranges varying from 12 to 1800 m (Table S3.3). Extractable P and K were relatively low in field B (Fig. S3.1), but step-wise multiple regression analyses indicated that there were no statistically significant correlations between the spatial variation of extractable P and K and spatial variations in wheat yields (not shown). We infer that it is unlikely that extractable (micro)nutrients were wheat yield limiting, although the level of some nutrients tended to be below recommended levels (Fig. S3.6, Table S3.4). We cannot exclude that spatial variations in available soil water and in the incidence of weeds and diseases have contributions to spatial variations in wheat yield. In summer, wheat roots may tap from shallow groundwater, which enters the root zone through capillary rise. This is one of the reasons for the rather stable wheat yields observed during 2015-2019, next to the good management by the farmers; the relatively low yield of Field A in 2016 was related to late sowing of summer wheat.

Spatial variations in soil bulk density may also contribute to spatial variations in crop yield, notably through its effect on root growth and the delivery of soil water and nutrients. Precision agriculture aims at addressing spatial variations in soil and crop performances, and thereby may contribute to increasing yield and resource use efficiency. Precision management relies on accurate measurements and spatially distinct areas that are sufficiently large to be managed (Diacono et al., 2013; Field et al., 2017). Spatial dependencies with a (very) short range and/or low stability over years are difficult to address. Application of precision management may be limited also by the often diffuse relationships between soil characteristics and crop yields, which makes inferences about spatial variations unreliable, and by the lack of appropriate tools to communicate between precision management techniques (Kempenaar et al., 2020).

3.3.3 Relationships between crop yield and soil properties

Multiple linear regression analyses indicated that spatial variations in wheat yield of field A were related to spatial variations in soil clay content, bulk density, and penetration resistance at 30-35 cm in 2015 and 2016 ($P<0.05$), but not in 2018 and 2019 (Table 3.2). These relationships may reflect a relationship between yield and soil water delivery to the crop (Libohova et al., 2018). Spatial variations in $CaCl_2$-extractable Mg content were related to spatial variations in wheat yield ($P<0.001$) in Field A in 2018, but we doubt whether this is a causal relationship (Table 3.2). No statistically significant relationships between within-field spatial variations in wheat yield and within-field spatial variations in soil characteristics were found for field A in 2019 ($P>0.05$, Table 3.2). Spatial variations in wheat yield were also significantly related to spatial variations in soil clay content in field B in 2015, but no significant relationships were found in 2016. However, spatial variations in wheat yield were not significantly related to spatial variations in soil bulk density or penetration resistance in field B, while it had a relatively high subsoil bulk density and a Relative Normalized Density above 1 (Tables 3.2, S3.2). Further, spatial variations in crop yield in field C were not significantly related to spatial variations in soil properties (Table 3.2). Evidently, the relationships between spatial variations in crop yield and soil characteristics were not stable over years, likely because of interactions as a result of differences between years in weather conditions. As a consequence, it will be difficult to address the spatial variations adequately through precision agriculture technology.

Table 3.2 *Coefficients (means ± standard deviations) of the multiple regression relationships between wheat yield and soil characteristics of fields A, B and C. Correlations coefficients (R^2) and degree of freedom (DF) are presented at the bottom of each block.*

	Field A (2015)	Field A (2016)	Field A (2018)	Field A (2019)
α (Intercept)	13.86±2.16***	9.17±1.47***	6.42±1.75***	7.96±2.4***
β_1 (Total N)	-0.54±1.06	-0.8±0.66	-0.43±0.86	1.1±1.59
β2 (SOM)	-0.35±0.51	0.35±0.32	0.01±0.41	0.22±0.66
β3 (Clay content)	0.1±0.04**	0.06±0.02*	0.002±0.032	-0.01±0.06
β4 ($CaCl_2$-extractable Mg)	0.02±0.01	-0.01±0.01	0.03±0.01***	-0.02±0.02
β5 (Bulk density in 30-35cm)	-2.73±1.36*	-0.84±0.88	1.19±1.1	2.19±1.79
β6 (Penetration resistance in 30-35cm)	-0.002±0.001	-0.003±0.001***	-0.001±0.001	0.001±0.001
R^2	0.23	0.48	0.23	0.16
DF	93	65	93	26
	Field B (2015)	Field B (2019)	Field C (2017)	Field C (2019)
α (Intercept)	16.94±4.87***	11.28±0.7***	10.3±1.96***	11.87±2.77***
β_1 (Total N)	-1.83±4.94	-0.34±0.71	-0.78±1.67	-2.47±2.36
β2 (SOM)	-1.28±1.71	0.21±0.24	0.48±0.72	0.83±1.02
β3 (Clay content)	0.31±0.15*	0.01±0.02	-0.02±0.04	0.01±0.06
β4 ($CaCl_2$-extractable Mg)	-0.01±0.03	-0.002±0.004	0.01±0.01	0.01±0.02
β5 (Bulk density in 30-35cm)	-0.71±2.36	-0.25±0.34	-0.95±0.98	-1.14±1.39
β6 (Penetration resistance in 30-35cm)	-0.001±0.003	-0.0005±0.0004	-0.0002±0.0014	0.001±0.002
R^2	0.18	0.06	0.03	0.02
DF	92	92	93	93

†) Multiple linear regression models (function lm() in R, James et al., 2013). The same as below.
††) Total N and SOM contents, g/kg; clay content, %; available Mg, mg/kg; soil (BD) bulk density, g/cm^3; penetration resistance (PR), kPa. The same as below.
†††) "" means 0.01<P<0.05, "**" means 0.001<P<0.01, "***" means P<0.001. The same as below.*

Few studies have related spatial variations in subsoil bulk density to spatial variations in crop yield, mainly because subsoil bulk density and spatial variations in subsoil bulk density cannot be measured easily (Horn et al., 1995b; Keller et al., 2017). Bölenius et al. (2018) found significant relationships between spatial variations in penetration resistance and spatial variations in crop yields, but these were strongly dependent on season and weather conditions. They concluded that single measurements of penetration resistance were insufficient to identify yield variations, apart from dry years. Usowicz and Lipiec (2017) found statistically significant negative relationships between spatial variations in cereal yields and spatial variations in top soil (0-10 cm) bulk density of a 1 ha large experimental field. The spatial dependence was strong and the range varied from 12 to 99 m between years (repeated measurements in the same field). However, subsoil compaction (or bulk density) was not measured. Usowicz and Lipiec (2017) found no statistically significant relationships between spatial variations in cereal yields and spatial variations in top soil (0-10 cm) bulk density of a 2.4 ha large farmers' field. Again, subsoil bulk density was not measured. Further, spatial variations in topsoil (0-20 cm) bulk density were negatively related to spatial variations in saturated hydraulic conductivity of soils at regional scale (140 km^2), while variations in bulk density were relatively small and only weakly spatial dependent (Usowicz and Lipiec, 2021).These studies clearly indicate that soil bulk density may be an important crop-yield influencing factor, but that data and information about the relationships between variations in subsoil bulk density and crop yield are often confounded by soil water contents.

3.3.4 Relationships between soil bulk density and potential CO_2 and N_2O emissions

Soil CO_2 respiration reflects soil biological activity (Avidano et al., 2005); it is primarily related to the amounts of metabolizable organic matter, temperature and soil aeration. Soil N_2O emission reflects the balance between N_2O production and consumption by micro-organisms in soil, and is related to the concentrations of ammonium (NH_4^+), nitrate (NO_3^-) and metabolizable organic matter, as well as to temperature and soil aeration (Bange, 2000; Kool et al., 2010; Wrage-Monnig et al., 2018). We hypothesized that spatial variations in potential CO_2 and N_2O emissions were related to spatial variations in soil bulk density, as soil bulk density affects soil aeration. Indeed, within-field variations in potential CO_2 emissions were often significantly related to within-field variations in soil bulk density in the subsoil at 30-35 cm in all four fields, and in two fields also at depth of 50-55 cm (Table 3.3). Also, variations in potential N_2O emissions were significantly related to variations in soil bulk density of the top soil in fields A and B and to variations in bulk density in the subsoil at depth of 30-35 cm in field A, and 50-55 cm of fields A and D (Table 3.3). Spatial variations in potential CO_2 and N_2O emissions were not related to spatial variations in the SOM content of the topsoil in any of the four fields.

Commonly, an increase in soil bulk density decreases CO_2 emissions and increases N_2O emissions (Bessou et al., 2010; Ruser et al., 2006; Sitaula et al., 2000; van Groenigen et al., 2005). Increases in soil bulk density decrease soil porosity and aeration, and thereby decrease soil respiration but increase N_2O production (or reduce N_2O diffusion and N_2O consumption rates). Changes in the ratio of soil CO_2 and N_2O emissions in response to changes in soil bulk density may thus provide insight into differential perturbations of soil C and N transformations. Frequency distributions of potential CO_2 and N_2O emissions were highly skewed in all fields, and therefore logarithmic values were used. The ratio of log CO_2 emissions to log N_2O emissions tended to decrease with an increase in soil bulk density, especially in field B (Fig. 3.5), the field with the highest mean bulk density and also with the highest coefficient of variation of the mean bulk density (Table S3.1). This indicates that potential N_2O emissions increased relative to potential CO_2 emissions with increasing bulk density. Further, the ratio of log CO_2 emissions to log N_2O emissions strongly decreased with bulk density following N application (Fig. 3.5). Emissions of N_2O in the top soil (5-10 cm) and sub soil (30-35 cm) increased by a factor of 2 to 5 following addition of $NaNO_3$, suggesting that the N_2O emissions were in part nitrate limited. Evidently, increases in N_2O emissions following N fertilization were much greater in soil with high bulk density than in soil with low bulk density. Note that the increased N_2O emissions in the top soil (0-5 cm) vanished after 6 days and that the peak in the subsoil at 30-35 cm occurred much later than in the top soil. No increases in N_2O emissions occurred following N application to the subsoil at 50-55 cm during the six-days measuring period (Fig. 3.5).

Our results provide further evidence that the current trend of increasing wheel loads in modern agriculture, which increase (sub)soil bulk density, may increase N_2O emissions from soil and especially also from the subsoil (Shcherbak and Robertson, 2019). Agriculture is a main source of greenhouse emissions and N_2O emissions form a significant fraction of the total GHG emissions from agriculture. Spatial variations in soil bulk density are likely also an important explanatory factor for the large spatial variations in N_2O emissions observed in the current study (Table S3.1) and in other studies (Robertson and Groffman, 2015).

***Table 3.3** Coefficients (means ± standard deviations) of the multiple regression relationships between potential N_2O emissions, potential CO_2 emissions and soil characteristics at depth of 5–10, 30–35, and 50–55 cm of the four fields. Correlations coefficients (R2) and degree of freedom (DF) are presented at the bottom of each block.*

	Field A	Field B	Field C	Field D
N_2O emission (5-10cm)				
α (Intercept)	-3.21±1.29*	-0.28±0.26	1.36±0.49**	1.63±2.29
β_1 (Clay content)	0.02±0.03	0.01±0.01	0.03±0.01***	0.03±0.08
β2 (SOM)	-0.61±0.4	0.1±0.11	0.2±0.2	-2.34±1.3
β3 (Bulk density in 5-10 cm)	3.38±0.82**	0.42±0.13**	-0.23±0.26	0.22±0.9
β4 (Penetration resistance in 5-	-0.001±0.002	-0.0003±0.0007	0.0004±0.0006	-0.001±0.005
β5 (Total N)	1.05±0.85	0.1±0.33	-0.83±0.45	3.87±2.78
R^2	0.25	0.21	0.15	0.08
DF	86	88	87	71
CO_2 emission (5-10cm)				
α (Intercept)	-17.41±10.34	-0.18±1.42	7.09±1.45***	7.17±2.16**
β_1 (Clay content)	-0.39±0.25	-0.02±0.05	-0.03±0.02	-0.02±0.06
β2 (SOM)	-5.01±3.26	-0.6±0.69	0.28±0.56	-1.42±0.75
β3 (Bulk density in 5-10 cm)	19.5±6.58**	1.07±0.72	-1.36±0.79	-2.42±1.11*
β4 (Penetration resistance in 5-	0.01±0.01	0.002±0.004	0.0001±0.0016	0.001±0.004
β5 (Total N)	12.44±6.95	2.74±1.92	-0.08±1.32	3.65±1.78*
R^2	0.23	0.07	0.07	0.09
DF	87	90	87	91
N_2O emission (30-35cm)				
α (Intercept)	-3.46±1.32*	1.15±0.37**	0.88±0.62	1.99±0.82*
β1 (Bulk density in 30-35 cm)	3.48±0.98**	-0.04±0.23	0.34±0.42	-0.35±0.52
β2 (Penetration resistance in	0.002±0.001	-0.0005±0.0003	-0.0003±0.0006	-0.002±0.001
R^2	0.17	0.04	0.01	0.04
DF	89	93	94	93
CO_2 emission (30-35cm)				
α (Intercept)	-	5.43±1.08***	19.34±1.84***	9.07±1.2***
β1 (Bulk density in 30-35 cm)	22.31±6.15*	-2.23±0.67**	-9.5±1.25***	-2.95±0.76***
β2 (Penetration resistance in	0.008±0.007	0.0007±0.0007	-0.0018±0.0016	-0.002±0.001
R^2	0.14	0.12	0.39	0.16
DF	95	94	93	91
N_2O emission (50-55cm)				
α (Intercept)	-5.11±2.28*	2.08±0.58***	3.26±1.28*	4.62±1.23***
β1 (Bulk density in 50-55 cm)	6.02±1.81**	-0.47±0.39	-0.84±0.8	-2.08±0.79**
β2 (Penetration resistance in	-0.001±0.001	0.00005±0.000	-0.0014±0.001	0.0002±0.0006
R^2	0.11	0.01	0.03	0.07
DF	95	95	92	96
CO_2 emission (50-55cm)				
α (Intercept)	-9.39±7.23	5.18±0.95***	5.2±1.41***	5.2±1.41***
β1 (Bulk density in 50-55 cm)	12.73±5.72*	-2.18±0.64***	-0.49±0.88	-0.49±0.88
β2 (Penetration resistance in	-0.003±0.004	0.0001±0.0005	0.00004±0.001	0.00004±0.001
R^2	0.05	0.12	0.01	0.01
DF	94	91	94	94

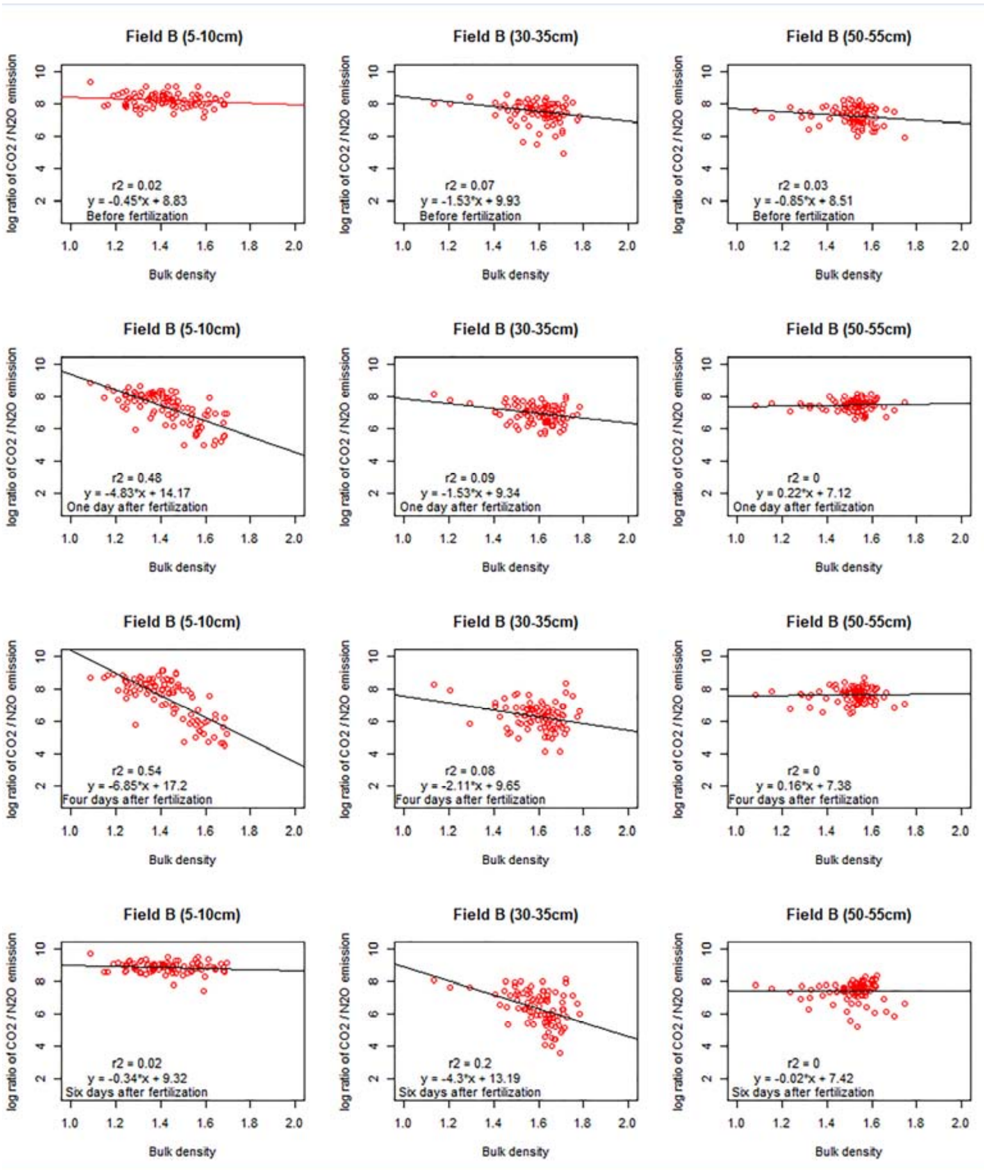


Fig. 3.5 *Relationships between soil bulk density (g cm^{-3}) and the ratio of potential CO_2 emissions and potential N_2O emissions (mg m^{-2} d^{-1}; log scale) for field B at three different depth intervals and at four different moments in time.*

3.4 Conclusions

Our initial hypotheses were only partly proven. We found significant variations in subsoil bulk density, which were spatially dependent, but the level of soil compaction appeared to be nowhere severe in the four fields. Further, within-field spatial variations in subsoil bulk density were related to within-field spatial variations in the potential emissions of CO_2 and N_2O, but not to variations in wheat yield.

Our random sampling approach yielded unbiased estimates of the spatial variations in subsoil bulk density and other soil properties within four fields, which were greatly different in shape and size. Most of these variations were strongly spatially dependent but the ranges were often relatively small, indicating that the scope for identifying distinctly different and manageable units was relatively small. Yet, semi-variograms proved to be an effective method to characterize spatial variations in both soil properties, soil processes and crop yields.

The mean bulk density of the subsoil in two fields was close to the suggested threshold of where bulk density affects soil functioning. Indeed, potential emissions of CO_2 and N_2O were significantly related to soil bulk density. The ratio of CO_2 emissions to N_2O emissions was negatively related to bulk density in both topsoil and subsoil, especially following N application, indicating that emissions of N_2O increased with an increase in soil bulk density. More studies are needed to find out how stable these relationships are over years, and how precision agriculture may address these relationships.

Spatial variations in wheat yield were only marginally related to soil properties. No statistically significant relationships were found between within-field spatial variations in (sub)soil bulk density and within-field spatial variations in wheat yield in any of the 8 field x year combinations analyzed. Variations in wheat yield were spatially dependent, and the ranges were on average larger than the ranges of soil properties, suggesting that spatial variations in wheat yield were mainly caused by other (management) factors. The near absence of a relationship between within-field variations in soil properties and within-field variations in wheat yield is likely also related to the fact that the within-field variations in soil properties were relatively small, that wheat is not a very sensitive crop to subsoil compaction, and that crop growth conditions are relatively good in the study area.

The farmers were not surprised by the findings of relatively high soil bulk density values in some fields, which they ascribed to effects of heavy harvesters and manure applicators. Increasingly, they use GPS-controlled trafficking to minimize the area and extent of soil compaction, as they are aware that there are as yet no easy-to-implement remediation measures for spatial variations in subsoil compaction.

Our study provides evidence that potential N_2O emissions (and the ratio of potential CO_2 emissions to potential N_2O emissions) is a more sensitive indicator for the effect of soil bulk density on soil functioning than wheat yield. The linear relationship between bulk density and the ratio of CO_2 emissions to N_2O emissions was apparent in both top soil (5-10 cm) and subsoil (30-35 cm). This linear relationship also suggests that there was no specific threshold for soil bulk density beyond which emissions change dramatically; instead emissions change gradually with an increase in bulk density.

Our results provide also evidence that an increasing soil compaction in modern agriculture contributes to increases in N_2O emissions from agricultural land and that these increases in emissions may emerge from the top soil as well as the subsoil. Future studies should consider N_2O emission factors as function of N fertilizers and (sub)soil bulk density.

Acknowledgement:
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 677407 (SoilCare project), and from China Scholarship Council (File No. 201408130093). We gratefully acknowledge the support from the farmers in the project H-Wodka, and from Eurofins-Agro.

Table S3.1 *Summary statistics of wheat yield and soil characteristics per field (means ± standard deviations). Means ± standard deviations of wheat yield per field are based on the measurements of the harvester; means of soil properties are based on 100 measurements per field (coefficient of variation (c.v.) =sd/mean).*

	Field A	*CV*	*Field B*	*CV*	*Field C*	*CV*	*Field D*	*CV*
	means ± sd	*(%)*	*means ± sd*	*(%)*	*means ± sd*	*(%)*	*means ± sd*	*(%)*
Soil pH (0-20 cm)	7.3±0.1	1	7.3±0.1	1	7.4±0.1	1	7.4±0.1	1
Clay (0-20 cm), %	16.9±4.8	28	21.9±3.1	14	24.1±4.3	18	18.8±1.9	10
SOM (0-20 cm), %	3.4±0.9	26	2.5±0.5	20	2.3±0.3	13	2.5±0.4	16
Total N (0-20 cm), g/kg	1.8±0.5	28	1.3±0.2	15	1.3±0.1	8	1.3±0.2	15
$CaCl_2$-extractable N (0-20 cm), mg kg^{-1}	96.3±22.0	23	75.4±9.8	13	77.0±8.2	11	76.9±9.9	13
$CaCl_2$-extractable P (0-20 cm), mg kg^{-1}	2.0±0.7	35	1.6±0.6	38	0.6±0.3	50	1.3±0.5	38
$CaCl_2$-extractable K (0-20 cm), mg kg^{-1}	120±28	23	107±27	25	60±12	20	135±28	21
Bulk density (5-10 cm), g cm^{-3}	1.34±0.10	7	1.43±0.14	10	1.43±0.10	7	1.53±0.15	10
Bulk density (30-35 cm), g cm^{-3}	1.36±0.08	6	1.60±0.11	7	1.46±0.10	7	1.58±0.10	6
Bulk density (50-55 cm), g cm^{-3}	1.32±0.09	7	1.52±0.10	7	1.53±0.07	5	1.55±0.08	5
Penetration resistance (5-10 cm), kPa	93±48	52	59±24	41	80±45	56	53±27	51
Penetration resistance (30-35 cm), kPa	214±75	35	134±96	72	133±66	50	78±59	76
Penetration resistance (50-55 cm), kPa	293±122	42	313±121	39	256±58	23	247±101	41
CO_2 emission (5-10 cm), mg m^{-2} d^{-1}	8.0±5.8	72	3.1±0.9	29	5.0±0.7	14	4.5±1.0	22
CO_2 emission (30-35 cm), mg m^{-2} d^{-1}	6.8±5.4	80	2.0±0.7	36	5.1±1.3	26	4.3±0.8	18
CO_2 emission (50-55 cm), mg m^{-2} d^{-1}	6.5±5.1	79	1.9±0.7	35	4.5±0.6	13	3.8±0.4	11
N_2O emission (5-10 cm), mg m^{-2} d^{-1}	1.4±0.7	51	0.9±0.2	21	1.1±0.3	23	1.8±1.2	66
N_2O emission (30-35 cm), mg m^{-2} d^{-1}	1.7±0.8	49	1.0±0.2	24	1.3±0.4	29	1.3±0.5	38
N_2O emission (50-55 cm), mg m^{-2} d^{-1}	2.5±1.7	65	1.4±0.4	27	1.6±0.5	34	1.4±0.6	43
Ratio of CO_2/N_2O (5-10 cm), mol mol^{-1}	6.0±4.8	80	3.9±1.5	38	4.8±1.5	30	3.4±1.8	54
Ratio of CO_2/N_2O (30-35 cm), mol mol^{-1}	3.7±2.8	75	2.1±0.9	44	4.2±1.9	44	3.6±1.5	41
Ratio of CO_2/N_2O (50-55 cm), mol mol^{-1}	2.7±2.3	83	1.5±0.6	43	3.2±1.5	47	3.0±1.0	34
Wheat yield (2015), Mg ha^{-1}	10.8±0.9	8	11.3±2.4	21				
Wheat yield (2016), Mg ha^{-1}	7.6±0.6	8						
Wheat yield (2017), Mg ha^{-1}					9.5±0.9	9		
Wheat yield (2018), Mg ha^{-1}	9.7±0.7	7						
Wheat yield (2019), Mg ha^{-1}	11.3±0.5	4	11.0±0.3	3	9.7±1.3	13		

Table S3.2 *Mean and median values and standard deviations (sd) of the Relative Normalized Density (RND) and of the relative porosity of four fields for three depth intervals.*

		RND			Relative porosity		
Fields		5-10cm	30-35cm	50-55cm	5-10cm	30-35cm	50-55cm
A	mean	0.85	0.86	0.83	1.24	1.22	1.26
	median	0.86	0.86	0.85	1.21	1.21	1.24
	sd	0.06	0.05	0.05	0.10	0.08	0.09
B	mean	0.92	1.03	0.98	1.15	0.99	1.07
	median	0.92	1.04	0.99	1.15	0.97	1.05
	sd	0.09	0.07	0.06	0.13	0.10	0.10
C	mean	0.94	0.95	1.00	1.15	1.12	1.06
	median	0.93	0.96	1.01	1.15	1.11	1.05
	sd	0.06	0.06	0.05	0.09	0.09	0.07
D	mean	0.97	1.00	0.98	1.06	1.01	1.04
	median	0.99	1.00	0.98	1.03	1.00	1.05
	sd	0.09	0.07	0.05	0.14	0.10	0.07

RND = actual soil bulk density / threshold bulk density;
threshold bulk density= 1.6 g/cm^3, when clay content is < 16.7%;
*threshold bulk density= 1.75 - 0.009 * clay content*, when clay content > 16.7%.
Relative porosity = actual soil porosity / threshold porosity. Threshold porosity = 0.4.

Table S3.3 *Semi-variogram coefficients of 0.01 M $CaCL_2$ extractable soil nutrients of the four fields.*

Fields	Soil nutrients	Model	Nugget, C_0 $(Unit)^2$	Sill, (C_0+C) $(Unit)^2$	Range, A (m)	Nugget ratio, $C_0/(C_0+C)$	R^2
A	N	Gaussian	0.02	0.09	561	0.20	0.93
	P	Gaussian	0.03	0.13	152	0.26	0.91
	K	Spherical	0.00	0.05	13	0.00	0.00
	Mg	Exponential	52.80	187.70	521	0.28	0.84
	Cu	Exponential	0.03	0.06	641	0.45	0.42
	Mn	Spherical	0.00	0.06	13	0.00	0.00
	Zn	Spherical	0.00	0.04	13	0.00	0.00
	Se	Gaussian	0.63	3.27	736	0.19	0.88
B	N	Exponential	40.40	217.80	1833	0.19	0.79
	P	Spherical	0.06	0.14	303	0.43	0.91
	K	Exponential	0.03	0.10	1276	0.30	0.81
	Mg	Spherical	84.00	237.00	611	0.35	0.82
	Cu	Spherical	0.02	0.06	611	0.26	0.86
	Mn	Linear	0.00	0.00	281	1.00	0.43
	Zn	Gaussian	0.00	0.01	33	0.00	0.27
	Se	Exponential	0.02	0.31	18	0.08	0.08
C	N	Linear	0.01	0.01	282	1.00	0.02
	P	Linear	0.13	0.13	282	1.00	0.33
	K	Exponential	0.01	0.04	17	0.15	0.03
	Mg	Exponential	0.00	0.03	24	0.11	0.24
	Cu	Linear	0.03	0.03	282	1.00	0.07
	Mn	Exponential	0.00	0.00	1833	0.34	0.22
	Zn	-	-	-	-	-	-**
	Se	Linear	0.02	0.02	282	1.00	0.30
D	N	Linear	100.7	100.7	282	1.00	0.16
	P	Spherical	0.01	0.12	20	0.07	0.16
	K	Spherical	0.00	0.04	16	0.00	0.01
	Mg	Exponential	3.61	27.31	32	0.13	0.19
	Cu	Spherical	0.00	0.03	19	0.03	0.07
	Mn	Exponential	0.00	0.35	12	0.14	0.00
	Zn	Spherical	0.00	0.00	22	0.15	0.01
	Se	Exponential	0.04	0.26	21	0.15	0.11

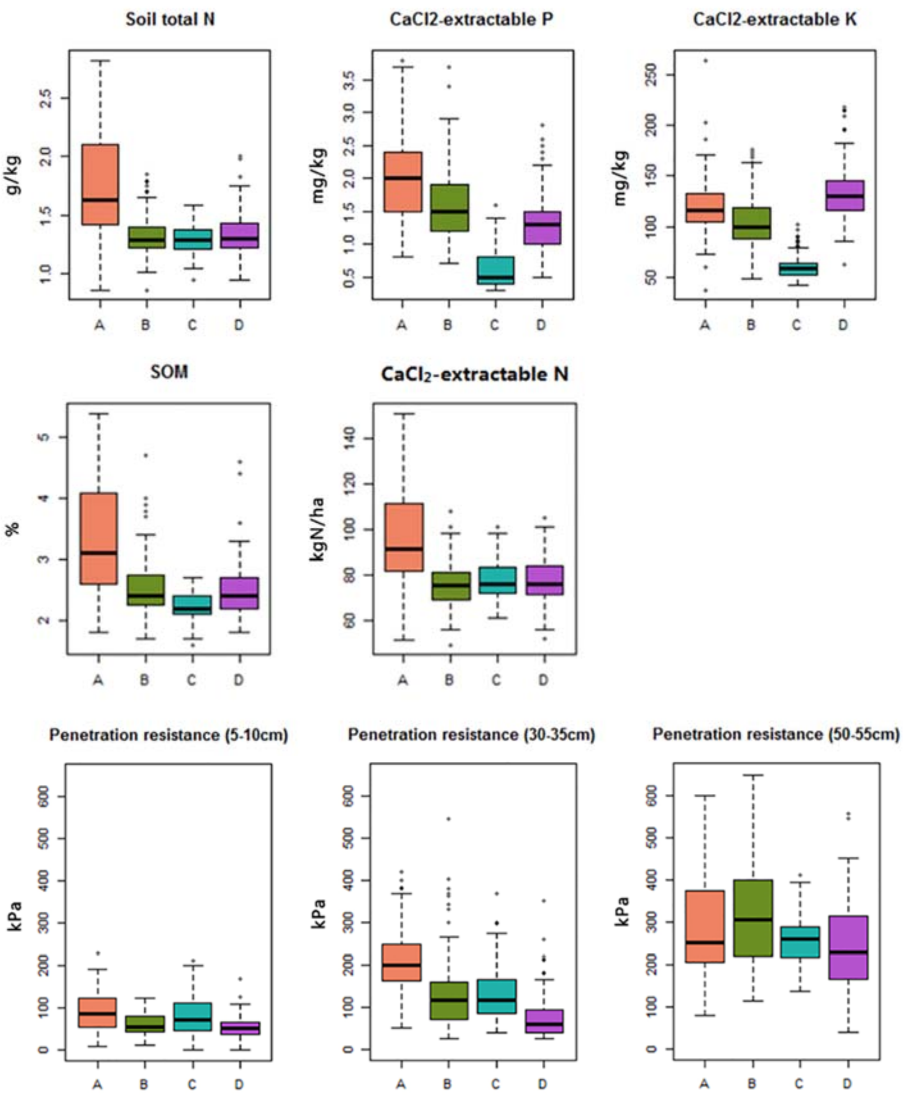
†) Normality tests were made before data analysis. Variables without normal distributions were log-natural transformed first. Results of Se and Mg in field A, B and D had normal distributions; other variables were all log-natural transformed before semi-variogram analyses.

††) Zn content in field C was at the same level everywhere in field C, because of it was below detectable level.

†††) Units: $CaCl_2$-extractable N, mg kg^{-1}; $CaCl_2$-extractable P: mg kg^{-1}; $CaCl_2$-extractable K: mg kg^{-1}; $CaCl_2$-extractable Mg: mg kg^{-1}; $CaCl_2$-extractable Cu: µg kg^{-1}; $CaCl_2$-extractable Mn: µg kg^{-1}; $CaCl_2$-extractable Zn: µg kg^{-1}; $CaCl_2$-extractable Se: µg kg^{-1}

Table S3.4 *Recommended range of soil nutrient test levels (Source: Eurofins Agro).*

Results		Unit	Result	Avg.*	Target value	low	rath.low	good	rath.high	high
macro nutrient										
	Total nitrogen stock	mg N/kg	2360							
	C/N ratio		10	11	13 - 17					
	N-supplying capacity	kg N/ha	130	90	93 - 147					
	Total sulphur stock	mg S/kg	540							
	C/S ratio		46		50 - 75					
	S-supplying capacity	kg S/ha	29	29	20 - 30					
	P-plant available	mg P/kg	1,2	2,1	1,0 - 2,4					
	P-soil stock	mg P_2O_5/100 g	47	52	27 - 47					
	Pw	mg P_2O_5/l	29							
	K-plant available	mg K/kg	148		70 - 110					
	K-soil stock	mmol+/kg	8,7		4,7 - 6,2					
	Ca-plant available	kg Ca/ha	510		208 - 486					
	Ca-soil stock	kg Ca/ha	12580		11440 - 17155					
	Mg-plant available	mg Mg/kg	99	100	50 - 85					
	Mg-soil stock	mmol+/kg	17,4		11,8 - 20,6					
	Na-plant available	mg Na/kg	26	25	35 - 50					
	Na-soil stock	mmol+/kg	1,3							
micro nutrients										
	Si-plant available	µg Si/kg	33380		6000 - 32000					
	Fe-plant available	µg Fe/kg	< 2040		2500 - 4500					
	Zn-plant available	µg Zn/kg	< 100		500 - 750					
	Mn-plant available	µg Mn/kg	< 250	260	1000 - 1300					
	Cu-plant available	µg Cu/kg	58		40 - 65					
	Co-plant available	µg Co/kg	< 2,5		25 - 50					
	B-plant available	µg B/kg	514	379	77 - 122					
	Mo-plant available	µg Mo/kg	12		100 - 5000					
	Se-plant available	µg Se/kg	6,8		3,5 - 4,5					
Physical										
	Acidity (pH)		7,4	7,3	> 6,4					
	C-organic	%	2,5							
	Organic matter	%	4,9	3,8						
	C-inorganic	%	0,98							
	Carbonate lime	%	7,3	4,4	2,0 - 3,0					
	Clay (<2 µm)	%	25	20						
	Silt (2-50 µm)	%	41							
	Sand (>50 µm)	%	22							
	Clay-humus (CEC)	mmol+/kg	245	183	> 183					
	CEC-saturation	%	100	88	> 95					
Biological										
	Soil life	mg N/kg	51		60 - 80					



†) Units:

Soil total N: g kg^{-1}; $CaCl_2$-extractable P: mg kg^{-1}; $CaCl_2$-extractable K: mg kg^{-1}

SOM: %; $CaCl_2$-extractable N: mg kg^{-1}; Penetration resistance: kPa

***Fig. S3.1** Boxplots of soil characteristics in four fields (A, B, C, D). Boxes indicate the upper (75%) and lower quartiles (25%) and the whiskers indicate the 5 and 95 percentiles. The line in the boxes indicate the median values. SOM and total N were determined by NIRS, 0.01 M $CaCl_2$-extractable N (NH_4^+ + NO_3^-), P and K by segmented flow analysis. Based on 100 samples per field.*

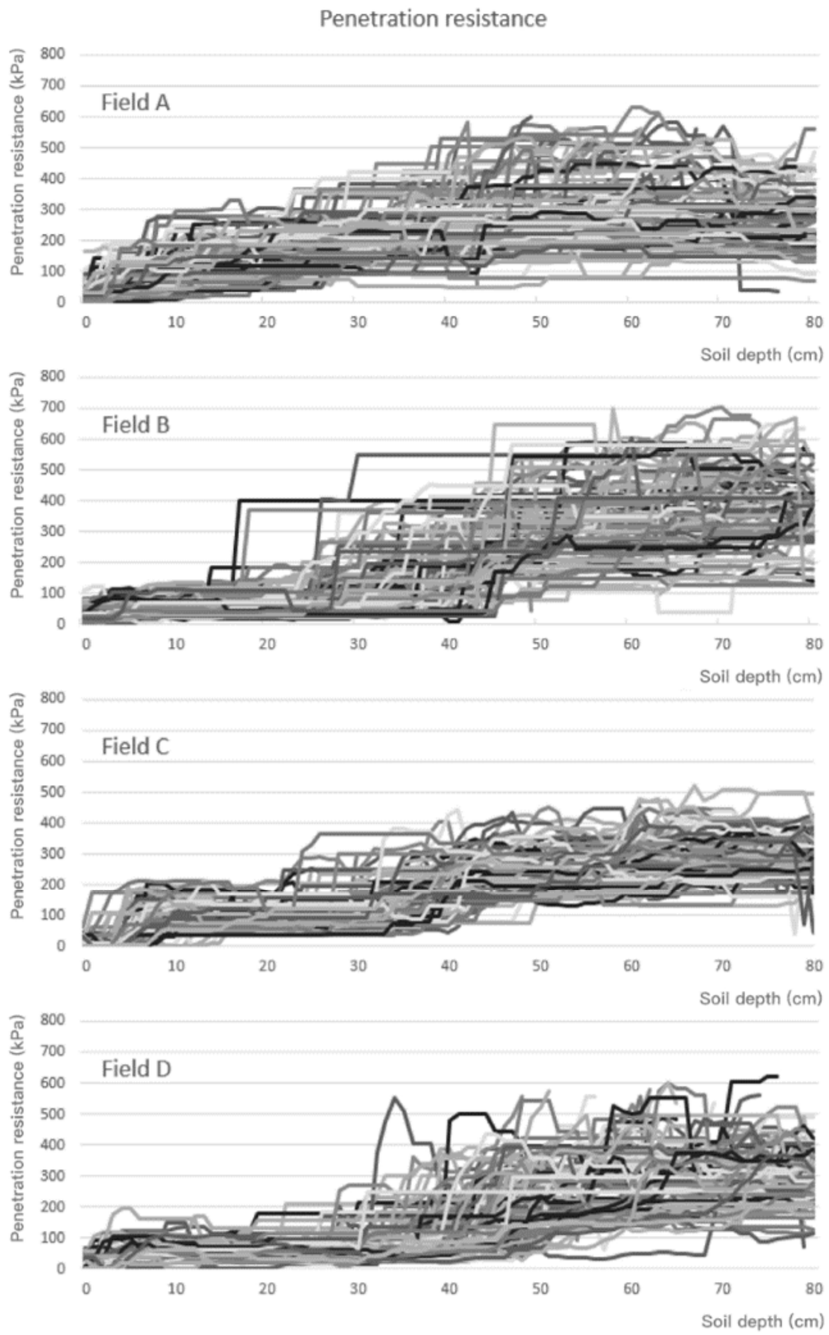


Fig. S3.2 *Soil penetration resistance as function of soil depth in four fields. Each line shows the average values of three recordings at one sampling site in the fields. In total, there were 100 sampling sites per field.*

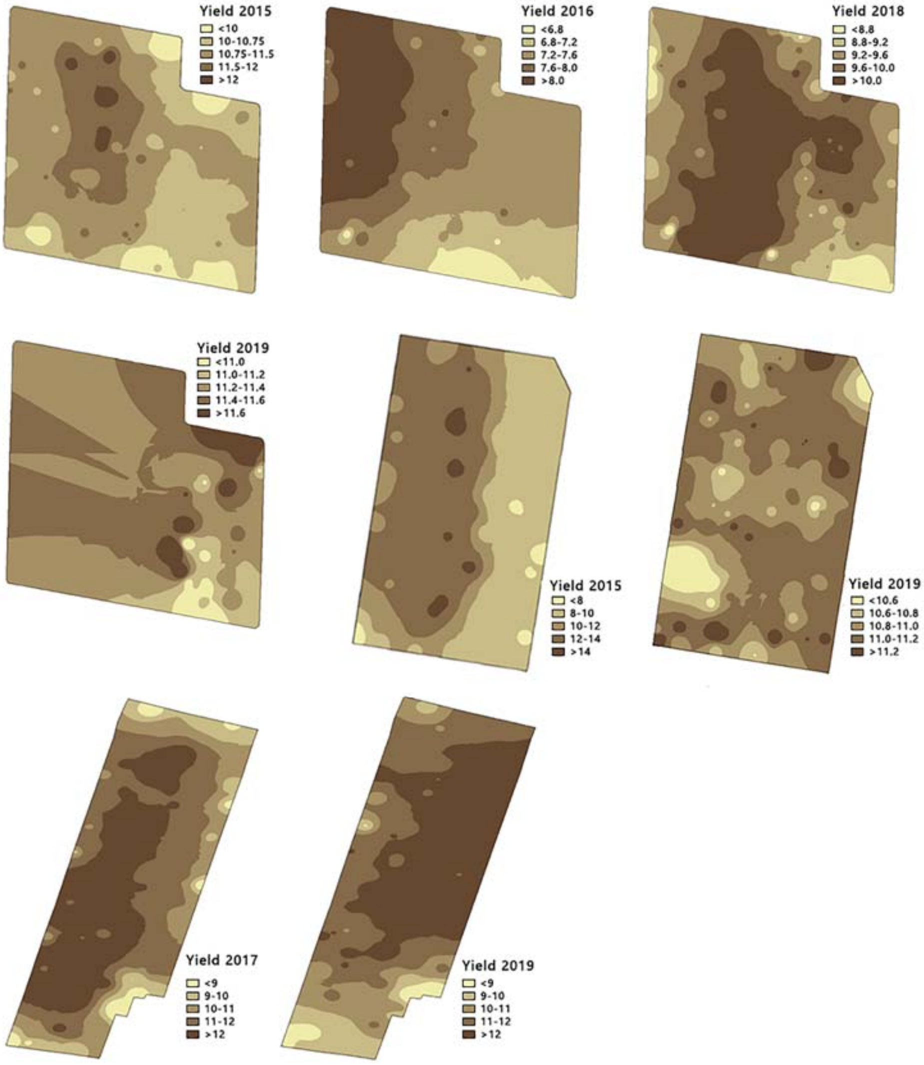
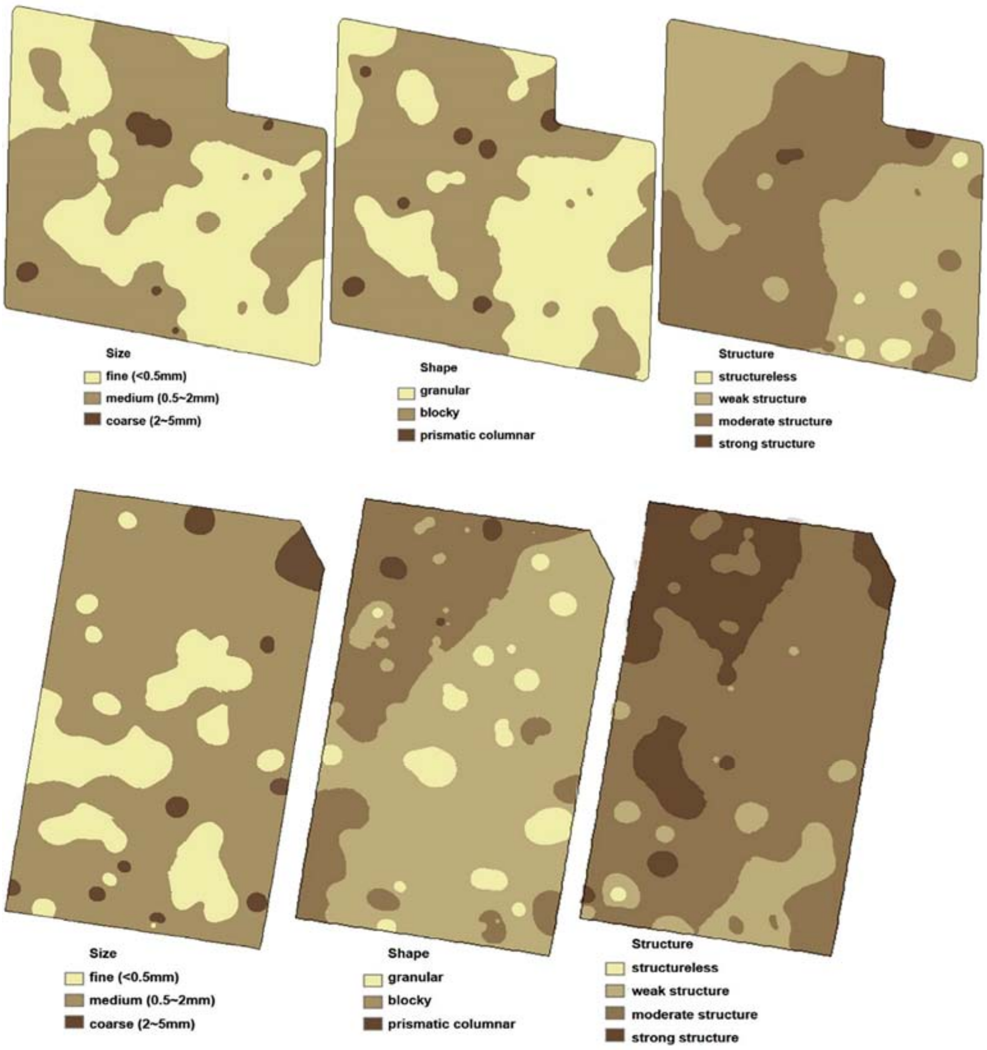


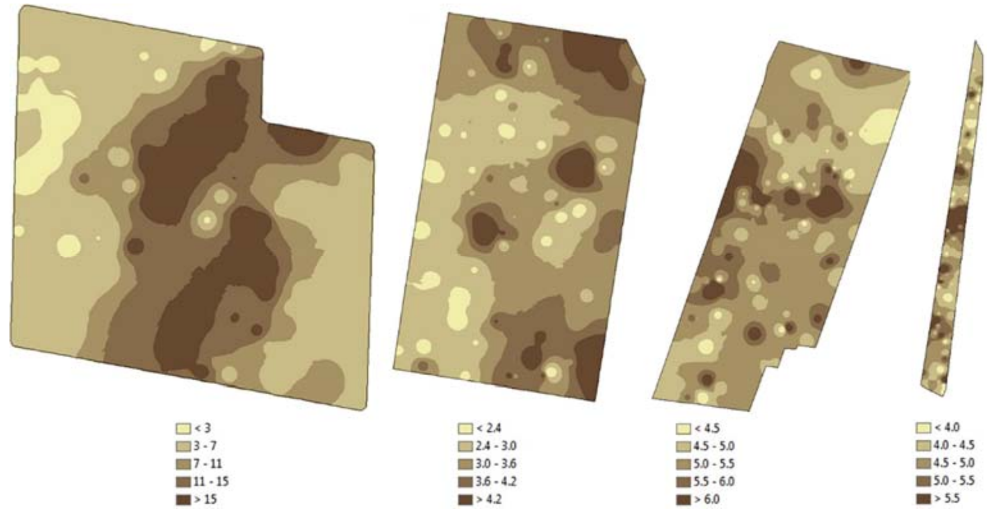
Fig. S3.3 *Maps showing the spatial distributions of crop yield in fields A, B and C in different years (units: Mg ha^{-1}). Spatial variations in wheat yields were displayed by ArcGIS, based on the Inverse distance weighted interpolation method (Lloyd, 2005). Note that the scaling differs between fields.*



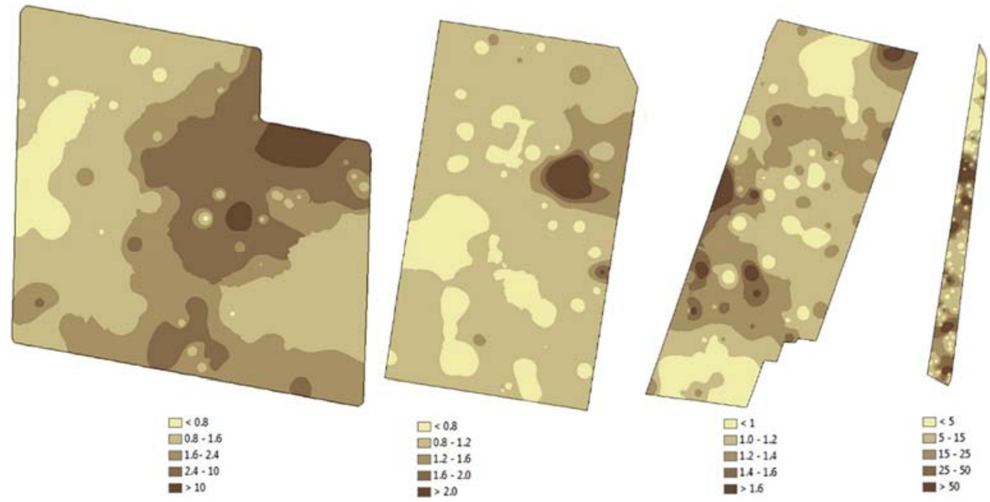
Legend

Soil size	Soil shape	Soil structure
1. fine (<0.5mm)	1. granular	1. structureless
2. medium (0.5~2mm)	2. blocky	2. weak structure
3. coarse (2~5mm)	3. prismatic, columnar	3. moderate structure
4. very coarse (>5mm)	4. platy	4. strong structure

Fig. S3.4 *Maps showing the spatial variations of the soil structure assessments of the top soil (0-5 cm) of fields A and B, in terms of (i) structure, (ii) shape of the soil aggregates, and (ii) size of the soil aggregates. See legend at the bottom of the figure. Based on 100 assessments per field. Spatial variations were displayed by ArcGIS, based on the Inverse distance weighted interpolation method (Lloyd, 2005).*



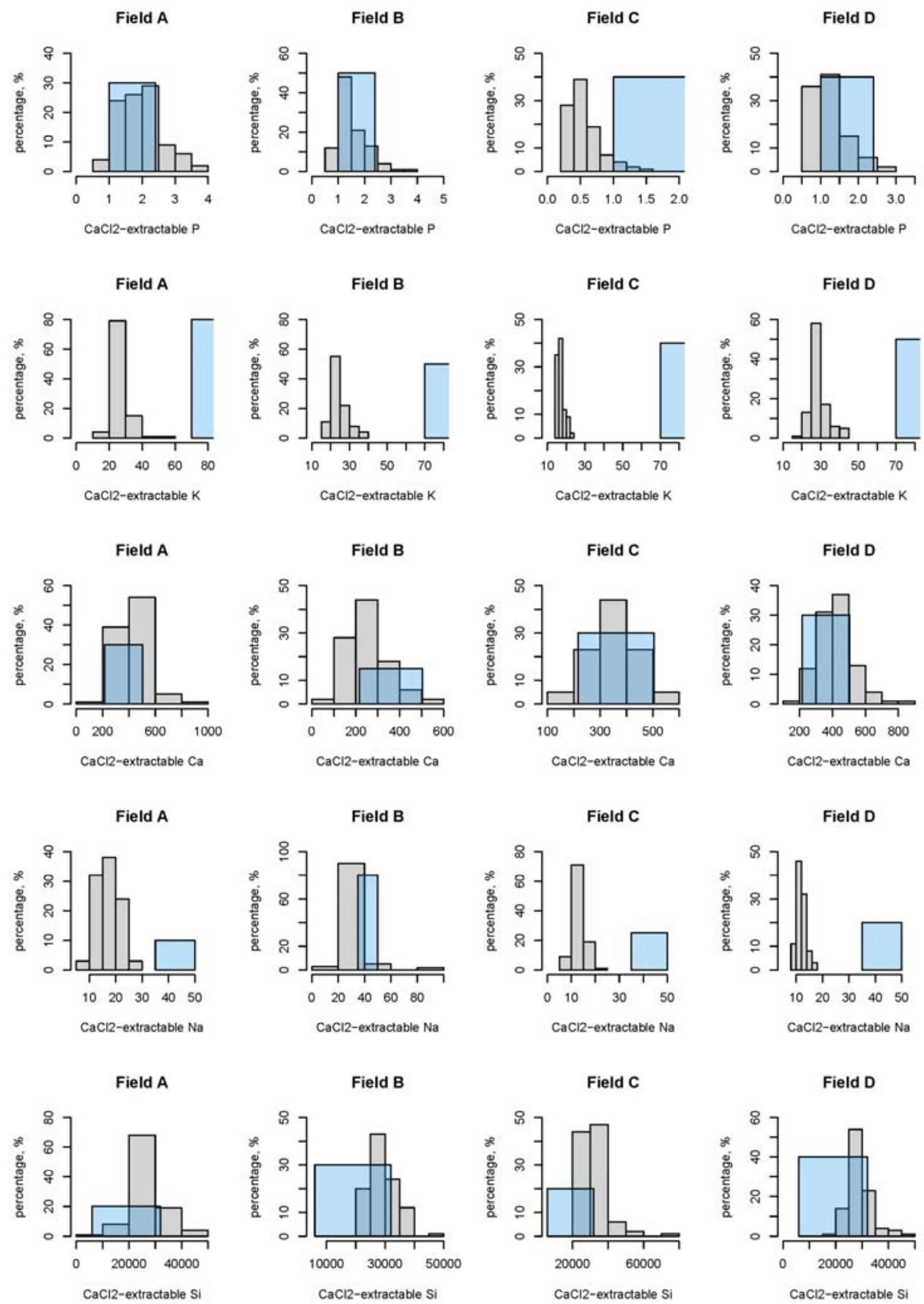
a. CO_2 emission (5-10 cm, mg m^{-2} d^{-1})

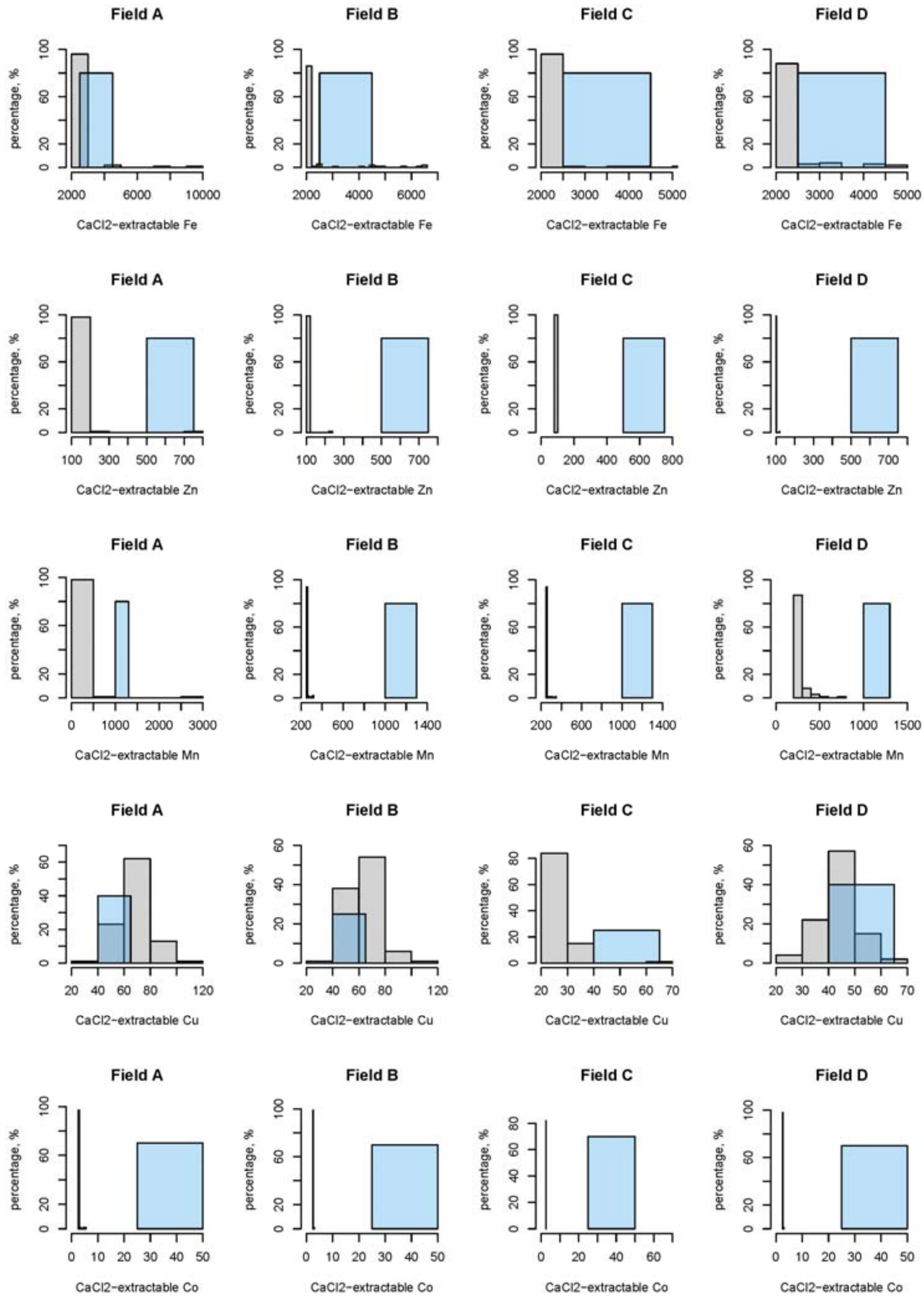


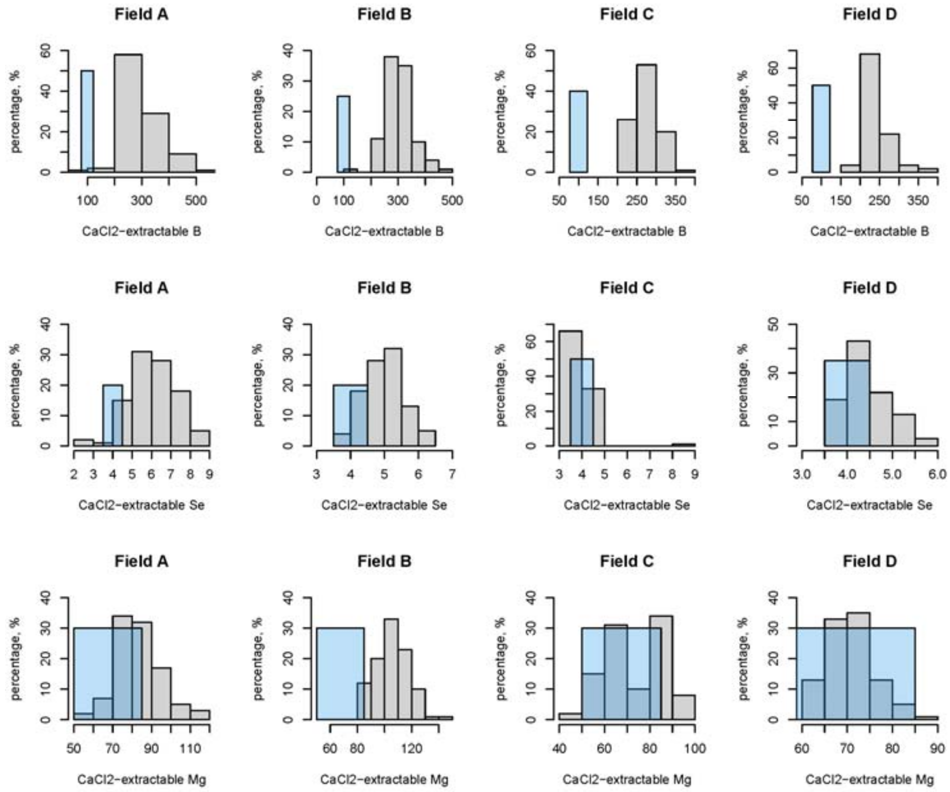
b. N_2O emission (5-10 cm, mg m^{-2} d^{-1})

Fig. S3.5 *Maps showing the spatial variations of soil respiration (CO_2 emission; upper four panels) and N_2O emission (lower four panels) in the top soil (5-10 cm) of four fields (A, B, C and D) measured following soil incubations. Spatial variations were displayed by ArcGIS, based on the Inverse distance weighted interpolation method (Lloyd, 2005). Note that the scaling differs between fields.*

Fig. S3.6 *Frequency distributions of 0.01 M $CaCl_2$ extractable (micro)nutrients in the top soil (0-20 cm) of four fields (A, B, C and D). Based on 100 samples per field. Recommendation ranges are indicated by the blue bars.*




Field A
Field B
Field C
Field D
percentage, %
CaCl2−extractable Fe
CaCl2−extractable Zn
CaCl2−extractable Mn
CaCl2−extractable Cu
CaCl2−extractable Co



Units:

CaCl$_2$-extractable P: mg kg^{-1}; CaCl$_2$-extractable K: mg kg^{-1}; CaCl$_2$-extractable Ca: kg ha^{-1};
CaCl$_2$-extractable Na: mg kg^{-1}; CaCl$_2$-extractable Si: µg kg^{-1}; CaCl$_2$-extractable Fe: µg kg^{-1};
CaCl$_2$-extractable Zn: µg kg^{-1}; CaCl$_2$-extractable Mn: µg kg^{-1}; CaCl$_2$-extractable Cu: µg kg^{-1};
CaCl$_2$-extractable Co: µg kg^{-1}; CaCl$_2$-extractable B: µg kg^{-1}; CaCl$_2$-extractable Se: µg kg^{-1}
CaCl$_2$-extractable Mg: mg kg^{-1}

4. Responses of cereal yields and soil carbon sequestration to four long-term tillage practices in the North China Plain

Current tillage practices in the important winter wheat–summer maize double cropping system of the North China Plain are under debate because of negative effects on soil quality and crop yield. Therefore, a long-term experiment was conducted from 2001 to 2018 to determine the effects of soil conservation practices on crop yield and soil quality. The treatments were imposed following maize harvest and prior wheat seeding, and were defined as follows: (1) moldboard ploughing (0–20 cm) following maize straw removal (CK); (2) moldboard ploughing (0–20 cm) following maize straw return (CT); (3) rotary tillage following maize straw return (RT); and (4) no tillage with maize straw covering the soil surface (NT). Wheat straw was chopped and spread on the soil in all treatments and maize seeded without prior tillage. Wheat yields were higher in CT than RT and NT treatments ($p < 0.05$); NT had 18% lower wheat yields than CT. No significant differences were found between treatments in summer maize yields. The soil organic carbon (SOC) content in the surface layer (0–5 cm) was higher in NT and RT compared to CT and CK. However, SOC content in the 10–20 cm and 20–30 cm layers were lower in NT and RT compared to CT and CK. Similarly, available phosphorus in the surface soil was higher in NT and RT than in CT and CK. but the opposite was true for the lower soil layers. SOC stocks (0–30 cm) increased in all treatments, and were initially faster in NT and RT than in CT and CK. However, SOC stocks were higher in CT than in other treatments at the end of the experiment. This finding indicates that no tillage and reduced tillage decreased both wheat yields and soil C sequestration over time; it also indicates that CT was the most robust in terms of crop yields and soil C sequestration.

Based on:

Chen, S., Yang, P., Zhang, Y., Dong, W., Hu, C., & Oenema, O. (2022). Responses of cereal yields and soil carbon sequestration to four long-term tillage practices in the North China plain. Agronomy, 12(1), 176.

4.1 Introduction

Soil tillage is conducted for several purposes: to prepare a seedbed for the next crop, to incorporate crop residues and fertilizers into the soil, to suppress weeds and to improve the bio-physical structure of the soil (Li et al., 2020). However, conventional tillage practices are under debate because of the increased soil organic matter decomposition and associated declines in soil organic carbon (SOC) stocks, soil biota and soil biodiversity (Aguilera et al., 2013; Madejón et al., 2009). Tillage practices are also implicated in risks of subsoil compaction (plough pan) and soil erosion (Busari et al., 2015).

Conservation tillage is defined as a field management approach that minimizes the intensity and frequency of tillage operations so as to achieve agronomic and environmental benefits, including an improvement in soil bulk density, soil aggregate stability, water use efficiency, and nutrient utilization (Chimsah et al., 2020). Indeed, conservation tillage may exert several beneficial effects, including a lower fossil energy use, greater SOC sequestration, and less soil compaction, erosion, and run-off (Gathala et al., 2015; Nouri et al., 2019; Piazza et al., 2020). Soil conservation includes different variants, including no tillage (NT) and reduced tillage (RT) or minimum tillage (MT), and these tillage practices can be combined, or not combined as the case may be, with crop residue mulching on the soil surface, crop rotation, cover cropping, and integrated pest and weed control practices. As a result, there is often a diversity in outcomes of soil conservation practices. For example, a meta-analysis of more than 600 field studies found that crop yields were significantly lower under no tillage compared to conventional till, when not combined with crop rotations and crop residue mulching (Pittelkow et al., 2015a). Yet, other studies found higher yields (Büchi et al., 2017; Peng et al., 2020), economic benefits (Kumara et al., 2020) and improvements in soil physical properties (Li et al., 2019b) under no till. No tillage appears to be less appropriate for continuous wheat compared to wheat in rotation with, for example, legumes (Macholdt and Honermeier, 2017). Further, the effects of conservation tillage on crop yields strongly depend on soil quality and climatic conditions (Lampurlanés et al., 2001). Conservation tillage had positive effects on crop yields in arid regions under rainfed conditions (Su et al., 2007; Taner et al., 2015). Conversely, conventional tillage gave higher yields than conservation tillage in humid climates and under irrigation (Martínez et al., 2008; Pittelkow et al., 2015a). Thus far, there has not been an agreement on crop yield changes under conservation tillage.

Soil organic carbon (SOC) is the largest carbon pool in terrestrial ecosystem, and plays an essential role in supporting soil biodiversity and biological activity, nutrient cycling, as well as regulating climate change (Stockmann et al., 2013). Conservation tillage was also promoted as an effective practice for increasing SOC (Blanco-Canqui and Lal, 2008; Ussiri and Lal, 2009). However, some studies found that there were no significant differences in SOC storage between no tillage and conventional tillage, when differences in the depth distribution of SOC and soil bulk density are accounted for (Luo et al., 2010; Ogle et al., 2019). The SOC balance is determined by the inputs of organic C into the soil (through crop residues, straw, stubble, roots and root exudates) and the outputs from the soil (through decomposition of organic matter, erosion and leaching of dissolved organic C) (Pedrotti et al., 2019). Soil tillage and crop residue management practices directly affect the balance between organic C inputs and outputs. Inputs of organic C depend on crop type and rotation, crop residue management, and tillage. The leaching of dissolved organic C is also a soil C loss pathway, but is negligible in most common systems and field conditions (Dong et al., 2009), except for situations with high rainfall or excessive irrigation, peat soils and/or with high inputs of highly soluble C substrates (Qin et al., 2017).

The North China Plain covers an area of 35 million ha and has a population of 130 million people. It is one of the most intensively cultivated regions in China (Du et al., 2010). Approximately 70% of the cultivated land has a double cropping system of winter wheat and summer maize, with a no tillage and moldboard ploughing combination (Liu et al., 2016). Moldboard ploughing is commonly applied to a depth of ~20 cm. Recently, rotary tillage to a depth of ~10 cm has also become common practice. Until the 2000s, straw was either used as animal feed and biofuel, or burned in the field. However, straw burning has been prohibited since 1990s (because of the smog); concentrates replaced straw as animal feed, while the increasingly used mechanization facilitated combine harvesting and straw chopping and return to the soil. As a consequence, the tillage and crop residue management changed. However, these practices increased the soil bulk density below 20 cm and created unfavorable growing conditions for wheat roots (Zhang et al., 2012). Hence, there is a continued search for improved tillage and straw management practices.

The main objective of this study is to determine the long-term effects of tillage and straw management practices on crop yield and soil C and nutrient accumulation in the winter wheat–summer maize double cropping system. We hypothesized that (1) replacing moldboard ploughing after the maize harvest by no tillage or rotary tillage may affect soil C sequestration, soil fertility, and thereby the crop yield in the long term, and that (2) removing maize straw from the field would not affect soil C sequestration much compared to maize straw return, because of the relatively large return of organic C via wheat straw, and the limited capacity of the soil to sequester C. We assumed that most SOC changes occurred in the 0–30 cm soil layer, because most of the roots of wheat and maize are in this layer and soil tillage and management practices mainly affect this layer (Drosos et al., 2020;

Du et al., 2010). Hence, soil sampling was limited to the top 30 cm of soil.

4.2. Materials and methods

4.2.1. Experimental site

The long-term experiment was conducted from October 2001 to June 2018 at the Luancheng Agroecosystem Experimental Station (37°53′N, 114°40′E; elevation 50 m) (Fig. S4.3), which is located on the piedmont of the Taihang Mountains on the North China Plain. The Luancheng experimental station is one of the stations of the China National Ecosystem Observation and Research Network and the Global Terrestrial Observation System. The experiment had a common and continuous double cropping system rotation of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.). Each year in early June, the winter wheat is harvested and maize is planted; while in early October maize is harvested and winter wheat is planted. There is no fallow period. The soil is a sandy loam and classified as entisol, with a clay content of 14% (Staff, 2014). The mean initial soil bulk density of the 0–20 cm layer was 1.53 g/cm^3, and the SOC content was 0.90 g/kg.

4.2.2 Experimental design and field management

In 2001, three tillage and crop residue management treatments were implemented: the conventional practice of moldboard plowing, rotary tillage (RT), and no tillage (NT) following the maize harvests. In 2004, the moldboard plowing plot was split into two subplots with different residue management strategies: half of the plot had chopped maize straw incorporation into the tillage layer (CT) and the other half had the maize straw removed (CK). A summary of the tillage and crop residue management practices of the four treatments is presented in Table 4.1. There were three replications for each treatment. Plot size was 560 m^2 (8 m × 70 m) for RT and NT and 280 m2 for CK and CT treatments.

At winter wheat harvest, wheat straw was mechanically chopped and evenly distributed on the soil surface as mulching material in all four treatments (common practice). At maize harvest, all straw was chopped and incorporated into the soil during tillage (common practice), except for the NT treatment where the straw was chopped and spread on the soil surface, and for the CK treatment where the straw was removed.

The fertilization and irrigation practices were identical in all four treatments and for both crops. Only urea and diammonium hydrogen phosphate (DAP) were applied. Before winter wheat sowing, the fertilizers were disseminated at a rate of 130 kg ha^{-1} of N and 121 kg ha^{-1} of P. However, DAP and urea were applied in bands at a depth of 5 cm in the seeding row of the NT treatment. In addition, both wheat and maize received 138 kg ha^{-1} of N as urea, shortly after jointing through top dressing. All plots received irrigation at sowing. Depending on rainfall and soil moisture condition, an additional three or four irrigations for wheat, and two or three irrigations for maize, were applied using a sprinkler system. Irrigation was applied when the soil moisture in the root zone declined to 60–65% of the field capacity. Generally, 40-50 mm water was applied in each irrigation.

Table 4.1 *Annual tillage and crop residue management practices per treatment *.*

	CK	**CT**	**RT**	**NT**
Tillage Before Wheat	Moldboard ploughing, tillage depth of 20 cm	Moldboard plough, tillage depth of 20 cm	Rotary tillage, tillage depth of 10 cm	No tillage
Tillage Before Maize	No tillage	No tillage	No tillage	No tillage
Wheat Seeding Pattern	15 cm between rows, 3–5 cm seeding depth	The same as CK	The same as CK	20 cm between rows, 10 cm inner row, 5 cm seeding depth
Maize Straw Management	Maize straw removed, root and stubble incorporated in the soil	Maize straw chopped (5–10 cm) and incorporated in the soil	The same as CT	Maize straw chopped (5–10 cm) and spread on the soil surface
Wheat Straw Management	Wheat straw chopped (5–10 cm) and spread on soil surface	The same as CK	The same as CK	The same as CK

** Rotary tillage has become common practice in North China Plain in recent years; the soil (0–10 cm) is broken into pieces through blades or teeth attached to the disks of a rotating drum.*

4.2.3 Data collection and monitoring

4.2.3.1 Grain yield

Wheat grain yields were measured in 3 m^2 plots following harvesting and threshing (with a thresher). After harvesting, the straw was chopped and returned to the field. Maize grain yields were measured in 10 m2 plots; Plants were manually cut down 10 cm above the soil surface, dried and weighted at harvest time, while the ears from the plants were manually harvested and threshed. Grains were air-dried to a moisture content of 13%, and their weights were recorded to obtain the final grain yields. The yield of each plot was calculated as the equivalent yield of the whole field, by the unit of t ha^{-1}.

4.2.3.2 Soil sampling and analyses

Soil samples were collected after winter wheat harvest in June every other year. Soil samples were taken by stainless steel rings of 100 cm^3, at the depths of 0–5, 5–10, 10–20, and 20–30 cm, using the same auger hole. The rings with soil samples were transported within 5 h to a temperature-conditioned room (4 °C) and stored until further analysis. Content of soil organic carbon (SOC) was measured by dichromate oxidation and subsequent titration with ferrous ammonium sulfate (Yeomans and Bremner, 1988).

Available soil P was measured by the hydrochloric acid–ammonium fluoride extraction/ molybdenum antimony colorimetry method (P-Olsen); available soil K was measured by ammonium acetate extraction and flame photometry (K-exch); and available N in soil was measured by the alkali hydrolysis diffusion method (Sparks et al., 2020). Soil bulk density was measured by the core method (ASAE standard, 1984).

4.2.3.3 Carbon input via straw return

The total carbon (C) input to the soil via straw return was calculated as:

*C input = grain yield * HI * C contents of straw*

Where HI is the harvest index; these values were determined for maize and wheat in 2005, 2007, 2008 and 2011. The average HI values for the CK, CT, RT and NT treatments for winter wheat were 0.50, 0.48, 0.47, and 0.47, respectively. The HI values for maize were 0.48, 0.47, 0.46, and 0.47, respectively. The carbon contents in wheat and maize straw were 0.405 ($g \cdot kg^{-1}$) and 0.421 ($g \cdot kg^{-1}$), respectively, as derived from literature (Chen et al., 2020).

4.2.3.4 Weather data

Daily weather data were obtained from a standard weather station, at approximately 50 m from the experimental site, and included the daily mean temperature, minimum temperature, daylight hours, and rainfall.

4.2.4. Statistical analysis

All data collected were statistically analyzed using ANOVA to test differences among treatments in crop yield, OM, SOC, AN, AP and AK. The means of the treatments were compared using Fisher’s LSD method at the 0.05 probability level. All analyses were conducted using SPSS statistical software (version 11.0, SPSS, Chicago, IL, USA). All figures were performed with R studio (version 3.2.1) and Office 2010.

4.3. Results

4.3.1 Climatic conditions

The mean temperature was 7.9°C during the wheat and 24.5°C during the maize season (Fig. S4.1). The average annual rainfall was 413 mm, with 60 to 80% during the maize season and 20 to 40% during the wheat season. The highest annual rainfall was 569 mm in 2008 and the lowest was 234 mm in 2016. The period from 2014 to 2018 was relatively dry and warm.

Table 4.2 *Annual wheat and maize grain yields (means ± s.d.) and mass of carbon (C) in aboveground residues returned to the soil (means ± s.d.) in a double cropping system with four tillage treatments during the period 2005–2018. The results of the statistical analyses are presented in the lower half of Table. See Table 4.1 for the tillage treatments.*

Treatments	**Wheat Yield *** **t ha^{-1} a^{-1}**		**Maize Yield *** **t ha^{-1} a^{-1}**		**Returned Residues *** **t C ha^{-1} a^{-1}**	
CK	6.2 ± 0.3 ab		7.4 ± 0.2 a		1.25 ± 0.09 c	
CT	6.3 ± 0.2 a		7.7 ± 0.4 a		2.83 ± 0.16 a	
RT	5.9 ± 0.1 b		7.7 ± 0.4 a		2.68 ± 0.19 b	
NT	5.2 ± 0.1 c		7.7 ± 0.3 a		2.64 ± 0.20 b	
	F	P	F	P	F	P
Tillage	36.0	0.00	0.8	0.45	24.5	0.00
Year	53.7	0.00	26.7	0.00	631.4	0.00
Soil x Year	3.5	0.03	4.2	0.02	2.39	0.19

** Different letters in the same column indicate significant differences at p< 0.05.*

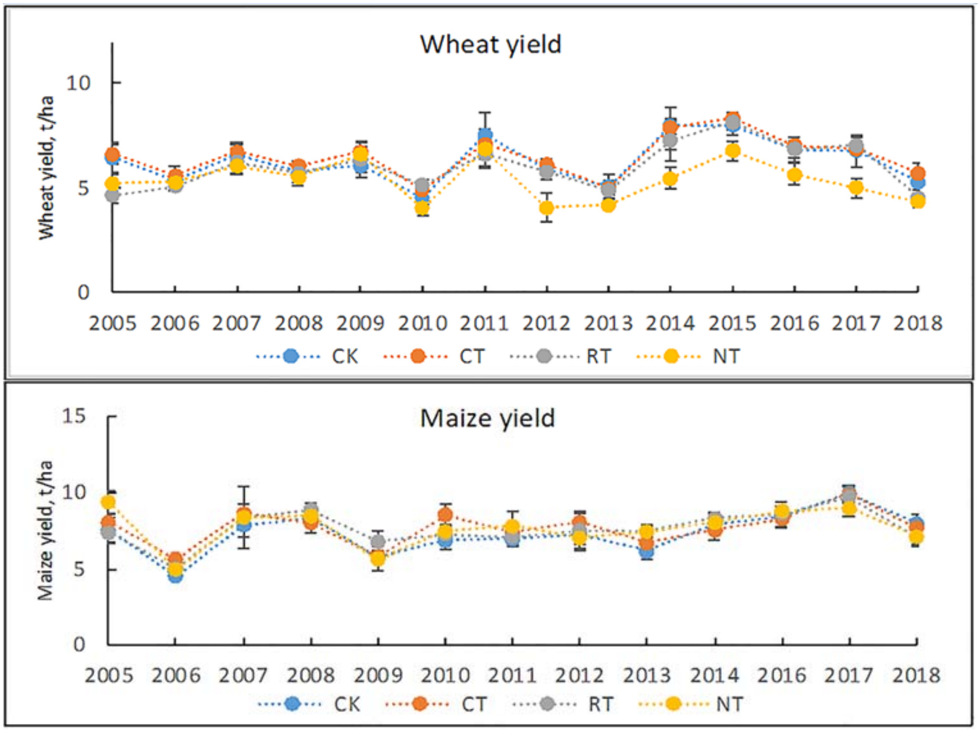


Fig. 4.1 *Grain yields of winter wheat and summer maize in a double cropping system with four tillage treatments during the period 2004 to 2018 (means ± standard deviations; bars represent standard deviations of the mean of six replicates). Colored lines between means are only meant to make differences between treatments more clear. See Table 4.1 for the tillage treatments.*

4.3.2 Wheat and maize yields

From 2005 to 2018, grain yields for winter wheat ranged between 4 and 8 Mg ha^{-1}, while grain yields for summer maize ranged between 5 and 10 Mg ha^{-1} (Fig. 4.1). The yield of winter wheat was significantly affected by tillage treatment and the experimental year. In addition, there was a significant interaction between Tillage and Year (Table 4.2). There were no significant trends in yield over time.

Mean wheat yields were significantly higher in the CK, CT and RT treatments than in the NT treatment ($p < 0.05$, Table 4.2). Furthermore, mean wheat yield was higher in CT than in RT ($p < 0.05$, Table 4.2). There were no significant differences between CK and CT, indicating that maize straw removal/return had no effect on wheat yield (Fig. 4.1). Mean maize yields did not differ between treatments ($p > 0.05$, Table 4.2). Differences between treatments in mean yields were ≤0.3 Mg ha^{-1}.

4.3.3 Total carbon input from straw return

The annual C input via straw return roughly ranged between 2.5 and 3.0 Mg ha^{-1} for the CT, RT and NT treatments, and between 1.0 and 1.5 Mg ha^{-1} for the CK treatment (Fig. 4.2). The mean annual C input at the CK treatment (1.25 Mg ha^{-1}) was significantly lower than at the other three treatments ($p < 0.001$, Table 4.2), while the mean annual C input at the CT treatment (2.83 Mg ha^{-1}) was significantly higher than those at the other three treatments ($p < 0.05$). There were no significant differences between RT and NT treatments.

4.3.4 Soil carbon contents and sequestration rates

Soil organic C (SOC) content increased in all treatments and all soil layers during the experimental period (Fig. 4.3). The mean SOC content decreased with depth and the rate of increase also decreased with depth. In the surface layer (0–5 cm), SOC content of NT treatment increased by 34% between 2005 and 2012, and then remained more or less constant at a level of 1.45 g kg^{-1} (Fig. 4.3). Note, that some differences in SOC content of the surface soil layer were already induced during the years 2001–2005, especially in the RT and NT treatments.

Stocks of SOC in the 0–30 cm soil layer increased rapidly from 2004 to 2012, Thereafter, the rate of increase slowed down in all treatments (Fig. 4.4). The CT treatment had higher levels of SOC stocks than the other three treatments from 2008 onwards, and reached 50 t/ha in 2018 (Table 4.3). The NT treatment had the highest C sequestration rate (0.99 kg ha^{-1} a^{-1}) during the first years (2001–2006), followed by the RT treatment (0.94 kg ha^{-1} a^{-1}), while CT treatment had the lowest C sequestration rate (0.56 kg ha^{-1} a^{-1}). However, the C sequestration rate continued to increase in the CT treatment, while the C sequestration in the RT and NT treatment slowed down during the period 2006 and 2018. As a result, the mean C sequestration rate was much higher in CT treatment (0.69 kg ha^{-1} a^{-1}) than in the RT and NT treatments (0.49 and 0.36 kg ha^{-1} a^{-1}, respectively) between 2001 and 2018 (Table 4.3). The CK treatment had the lowest mean C sequestration rate (0.25 kg ha^{-1} a^{-1}).

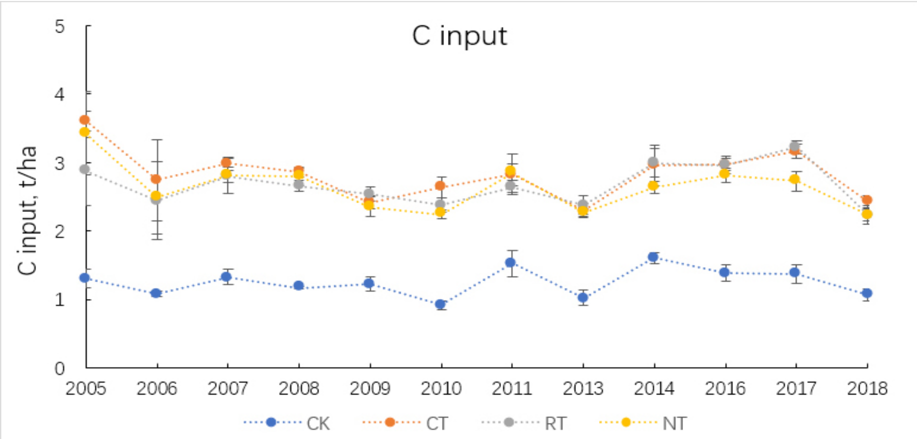


Fig. 4.2 *Organic carbon input (t/ha) into the soil from aboveground residues of winter wheat and summer maize in a double cropping system with four tillage treatments during the period 2004 to 2018. Bars represent standard deviations of the mean of six replicates. See Table 4.1 for the tillage treatments.*

4.3.5 Available soil nutrients

The available soil N (AN) remained more or less constant during the experimental period and did not differ much between treatments (Fig. 4.5a). It decreased slightly with depth. The RT and NT treatments tended to have the highest AN content at a depth of 0-5 cm depth, and the lowest AN content at a depth of 20-30 cm, compared to the CK and CT treatments.

The available soil P (P-Olsen) exhibited large inter-annual fluctuations, especially in the top 5 cm of the soil, but showed no clear trends over time; it decreased with increasing depth. The treatments, RT and CK, tended to have the highest AP content at a depth of 0–5 cm (Fig. 4.5b).

The available soil K (K-exch) also displayed relatively large inter-annual fluctuations, but without clear trends over time. AK decreased with increasing depth. There were no clear differences between treatments in AK (Fig. 4.5c).

The ratios (wt/wt) of AN, AP and AK displayed some clear patterns (Fig. S4.2). The mean ratio of AP/AN strongly decreased with increasing depth, suggesting a relative accumulation of P in the topsoil. The ratio of AK/AN was within a narrow range of 0.8 to 1.0 for all four depths, suggesting a similar availability and mobility of N and K. The ratios of AP/AN were relatively low in NT. Conversely, the ratios of AK/AP were relatively high in NT and low in CK and CT. This is the opposite to our expectations, as it suggests no preferential accumulation of P in the surface soil of NT (no tillage).

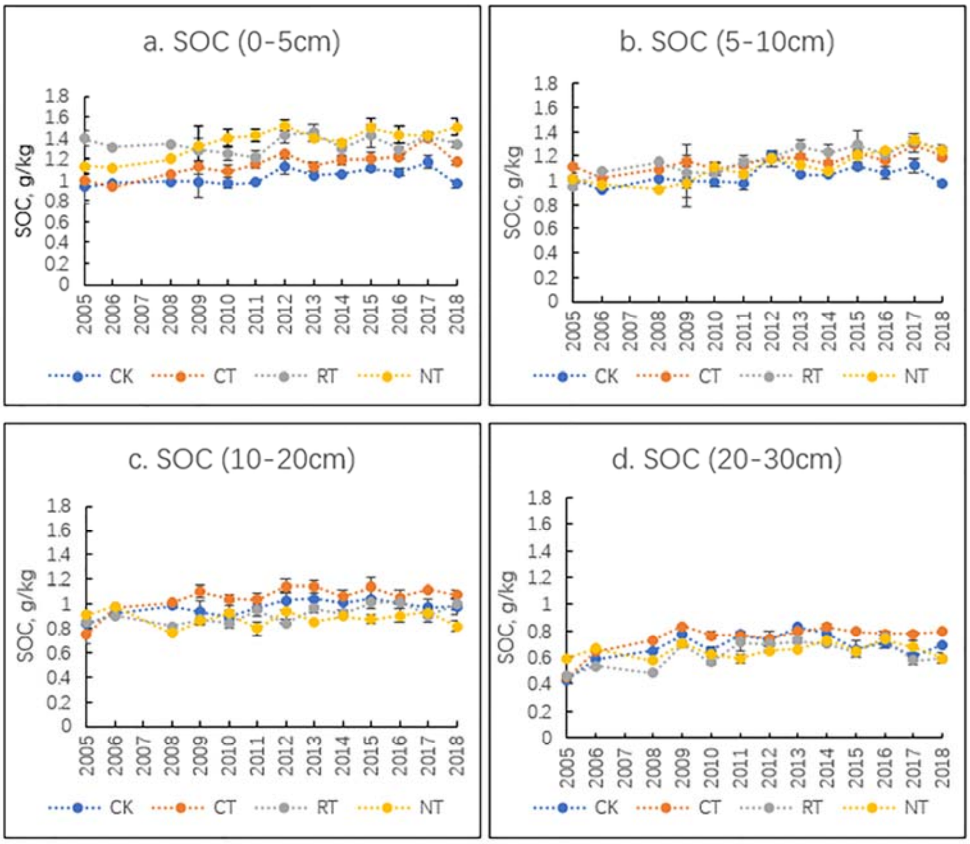


Fig. 4.3 *Soil organic carbon content (SOC, g kg^{-1}) of the 0–5 cm (a), 5–10 cm (b), 10–20 cm (c), and 20–30 cm (d) soil layers in a double cropping system with four tillage treatments, during the period 2004 to 2018 (means ± standard deviations; bars represent standard deviations of the mean of six replicates. See Table 4.1 for the tillage treatments.*

4.3.6 Soil bulk density

Soil bulk density ranged between 1.2 to 1.4 g cm^{-3} in the 0–5 cm soil layer and between 1.5 to 1.8 g cm^{-3} in the 20–30 cm soil layer (Fig. 4.6). Hence, bulk density increased with depth. The inter-annual variations were larger than the differences between treatments. There were no clear trends over the time. The relatively high bulk density in the 20–30 cm layer, and to a lesser extent in the 10–20 cm soil layer was observed in all treatments, suggesting that this high bulk density was not related to the tillage treatments.

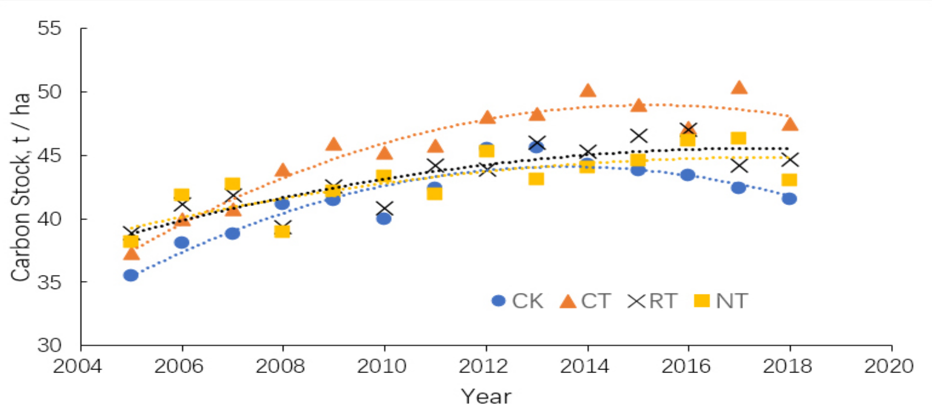


Fig. 4.4 *Changes in soil carbon stocks (t ha^{-1}) in the topsoil (0–30 cm) of four tillage treatments during the period 2004 to 2018. Dotted lines represent trend lines. See Table 4.1 for the tillage treatments.*

Table 4.3 *Soil C stocks (0–30 cm) in the four treatments in 2001, 2006, 2011 and 2018, and estimated C sequestration rates in the four tillage treatments for three periods. See Table 4.1 for the tillage treatments.*

	CK	CT	RT	NT
		C stock in 0–30 cm soil layer, t ha^{-1} *		
2001	38.1	37.1	36.4	36.9
2006	38.0 bc	39.9 abc	41.1 ab	41.8 a
2011	42.3 ab	45.8 a	44.2 b	41.9 ab
2018	41.5 c	48.9 a	44.7 b	43.0 b
		C sequestration rate, kg C ha^{-1} a^{-1} *		
2001–2006	−0.01 c	0.56 b	0.94 a	0.99 a
2001–2011	0.43 b	0.87 a	0.78 ab	0.50 b
2001–2018	0.25 c	0.69 a	0.49 b	0.36 bc

** Different letters in the same row indicate significant differences at $p< 0.05$.*

4.4. Discussion

4.4.1 Depth-distributions of carbon and nutrients in soil

The winter wheat–summer maize double cropping system of the North China Plain is productive, also providing much straw and stubble (Han et al., 2018). Crop yields increased steadily during the last few decades, through the use of improved germplasms, fertilizers and pesticides (Jaggard et al., 2010). Until recently, straw from the double cropping system was used as animal feed and biofuel, or burned in the field (Xin-sheng et al., 2011), indicating that the soil C stock was replenished by input from stubble and roots only. However, the traditional mixed-crop livestock farm has rapidly disappeared during the last few decades (e.g., (Jin et al., 2020), and is being replaced by specialized livestock farms, which use mainly concentrated feed and little or no straw, and specialized crop production systems that produce for the market. Additionally, the use as biofuel has rapidly decreased, because a ban on crop residue burning, both in the field and in the homestead (Qu et al., 2012), was introduced from 2000 onwards; many farmers are still struggling to manage maize straw. As a result, increased amounts of crop residues are available to feed the soil and SOC stocks increased in the North China Plain during the last few decades (Kong, 2014; Wang et al., 2020). This is also apparent in the results of our experiment; SOC stocks increased in all treatments but with large differences between treatments (Fig. 4.4).

There are two possible main reasons for the relatively high soil C sequestration. First, the soil was 'carbon deficient' due to thousands of years of conventional soil cultivation and cropping in the North China Plain (Cheng et al., 2005), concomitant with straw removal (for use as biofuel or animal feed) or straw burning. Secondly, increasing amounts of crop residues have become available due to the increasing crop yields in recent decades, increasing the return of crop residues to the soil. This suggest that SOC sequestration rates were strongly influenced by changes in C inputs over time.

Tillage treatments significantly affected the depth distribution of C in soil, and to a lesser extent, the depth distributions of AN, AP and AK. Our results support the claim that, especially no tillage (NT) and reduced tillage (RT) combined with straw return, lead to the enhanced stratification of SOC compared to the conventional practice (CK treatment) of annual moldboard ploughing and the removal of maize straw.

The SOC content of the 0–5 cm soil layer, and to a lesser extent, of the 5–10 cm soil layer were higher in RT and NT than in CK and CT treatments, while the opposite was true for the 10–20 and 20–30 cm soil layers (Fig. 4.3). This difference in SOC stratification with depth is likely the combined result of (i) a difference between treatments in tillage following the maize harvest; (ii) maize straw removal in the CK treatment; and (iii) lower wheat yields in the NT, to a lesser extent in the RT treatment, compared to the other treatments (Coppens et al., 2006; Giacomini et al., 2007). The SOC content of the 10–20 and 20–30 cm soil layers were significantly higher at the CT treatment than at the RT and NT treatments at the end of the experiment. This suggests that the difference between CT and RT/NT in crop yield and associated root biomass was an important factor for the difference in content SOC between the 10–20 and 20–30 cm soil layers.

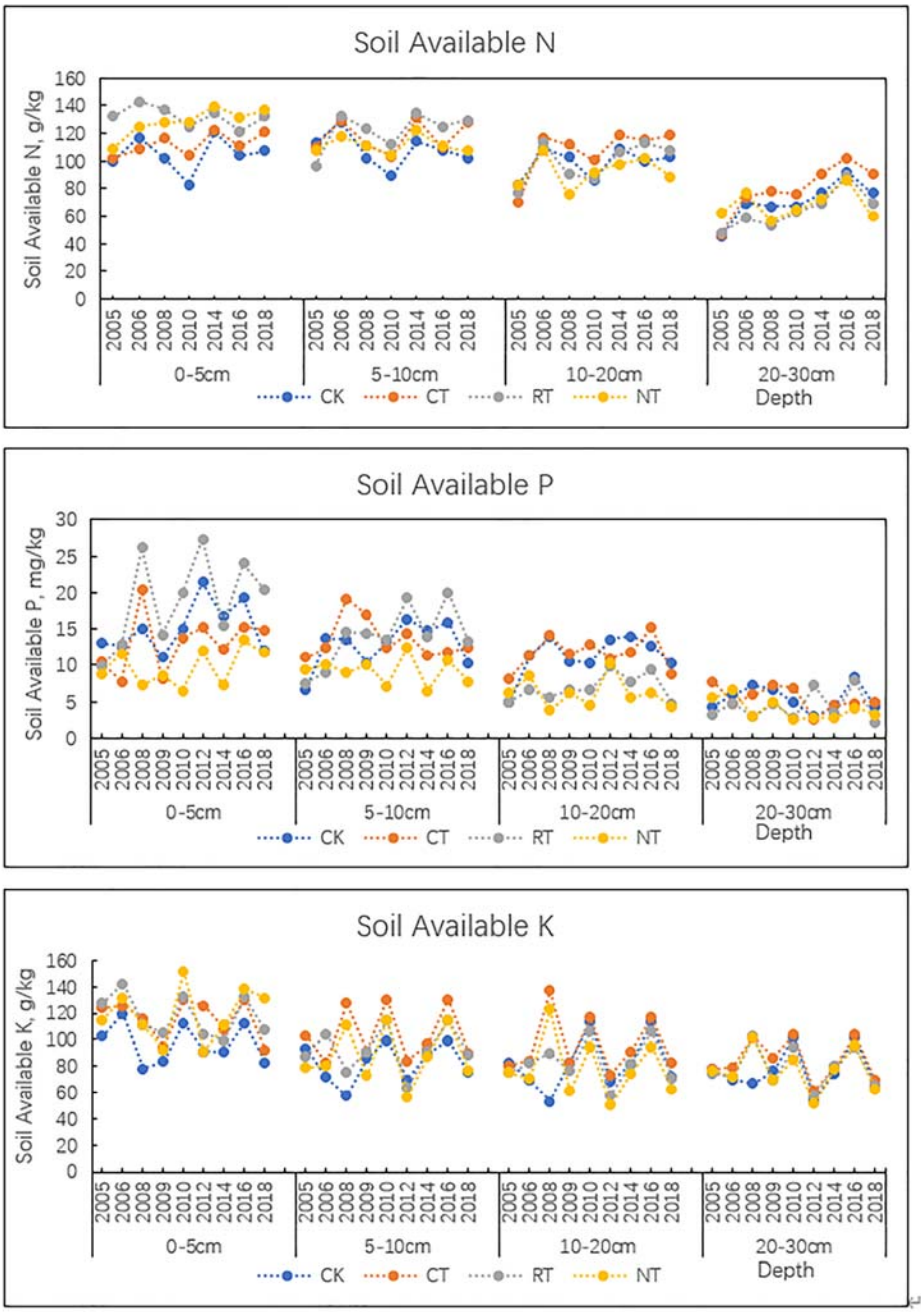


Fig. 4.5 *Available soil nitrogen (a. AN, g kg* $^{-1}$*), soil phosphorus (b, AP, mg kg*$^{-1}$*) and soil potassium (c. AK, g kg*$^{-1}$*) in the 0–5, 5–10, 10–20 and 20–30 cm soil layers in a double cropping system with four tillage treatments during the period 2004 to 2018. See Table 4.1 for the tillage treatments.*

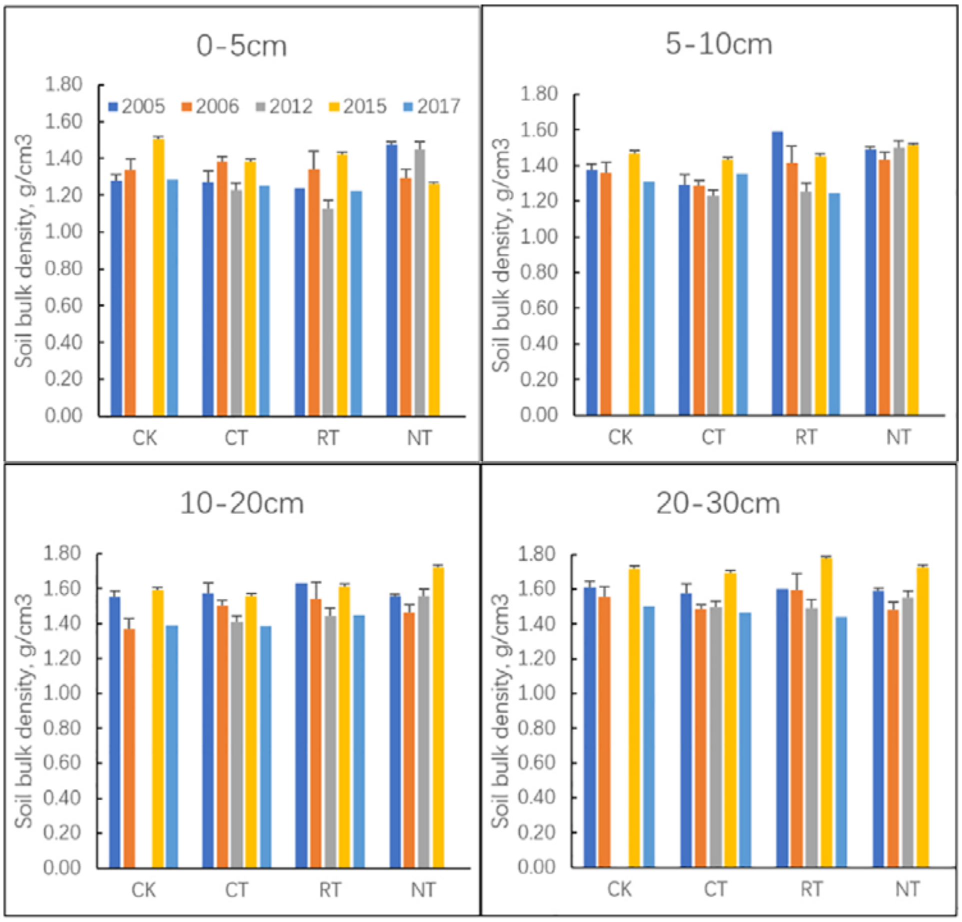


Fig. 4.6 *Soil bulk density (g cm⁻³) of the 0–5, 5–10, 10–20 and 20–30 cm soil layers of a double cropping system with four tillage treatments in 2005, 2006, 2012, 2015, and 2017. Line bars represent the standard deviation of the mean of six replicates. See Table 4.1 for the tillage treatments.*

The relative enrichment of AP in the 0–5 and 5–10 cm soil layers and the relative depletion of AP in the 10–20 cm of the NT and RT treatments compared to the CK and CT treatments reflect the low mobility of P in soil. Phosphorus is mixed through the soil by soil cultivation and possibly bioturbation, but little by leaching and diffusive transport. These results are consistent with results of previous studies showing that AP was concentrated in surface soil under conservation tillage management due to lower soil disturbance (Cade‐Menun et al., 2010; Vu et al., 2009). The relative enrichment of P in the soil surface layers was also attributed to the retention of P in the accumulated SOC (Weil et al., 1988; Zibilske et al., 2002). Though this is probably also true for our experiment, the greatest enrichment of AP in the surface layers of the NT and RT treatments likely resulted from the surface application

of the DAP fertilizers, although DAP was applied in bands at a depth of 5 cm in the NT treatment. The annual application of 121 kg P ha^{-1} exceeded the withdrawal of P with harvested wheat and maize (not shown), indicating that there was a continuous enrichment of P in the soil. However, this was not clearly reflected in the results of the AP analyses.
There were no significant differences between the tillage treatments in the AK content, which confirms that the tillage method has little or no influence on the distribution of extractable K (Matowo et al., 1999; Zuber et al., 2015). Relative increases in exchangeable K in soil surface layers of the RT and NT treatments may be related to the release of K from K-rich straw and stubble (Lozano-García and Parras-Alcántara, 2014; Martin-Rueda et al., 2007). The relative low content of AK in the CK treatments supports this, as the maize straw was removed from the field in this treatment (Fig. 4.5).

4.4.2 Responses of maize and wheat grain yields to tillage treatments

Earlier reports indicate that no-tillage agriculture decreased wheat yields in the North China Plain (Kan et al., 2020; Li et al., 2015) and elsewhere (Amato et al., 2013; Känkänen et al., 2011), dependent on crop rotation and crop residue management. Our results support this conclusion, indicating that no tillage lowers wheat yields not only in rainfed conditions but also under irrigation. However, wheat yields of the NT treatment were similar to those of the CT and RT treatments during the first years (Fig. 4.1), indicating that the negative effect of NT on wheat yield developed over time. We do not exclude the possibility that a lower soil temperature in the NT treatment, compared to the other treatments, played a role in reducing wheat yields (Eckert, 1984; Graven and Carter, 1991; Herbek et al., 1986). A poorer germination and tillering due to soil compaction at a depth of 5–30 cm, and a poorer access of wheat roots for the applied nutrients, may also have played a role. We noticed that the growth and development of the wheat plants were delayed in the NT treatment compared to the other treatments (not shown).

No tillage and the surface mulching of crop residues may reduce soil evaporation, and thereby conserve soil water in dryland agriculture, and as a result may enhance crop yield. However, available soil moisture was not a limiting factor in our study because of the imposed irrigation management. It was observed that the wheat yield decline with no tillage was relatively large at low rates of fertilization (Alvarez and Steinbach, 2009; Lundy et al., 2015; Ogle et al., 2019). Though the N and P fertilization rates were relatively high (common practice), Olsen P was relatively low (5 to 12 mg/kg) in the soil of the NT treatment (Fig. 4.5), and this may have contributed to the relatively large wheat yield decline in the NT treatment. Amounts of AN and AK did not differ much between treatments (Fig. 4.5).

Maize yields were not affected by tillage treatments (Fig. 4.1). This was in contrast with results of previous studies, which revealed that no tillage had a relatively large depressive effect on maize yields (Pittelkow et al., 2015a; Rusinamhodzi et al., 2011; Toliver et al., 2012). However, our tillage treatments were imposed after the maize harvest and before wheat seeding, while no tillage with surface mulching was applied at all treatments after the wheat harvest and before maize seeding. Evidently, the tillage treatments did not have a direct effect on maize. There are three additional possible reasons why NT (and RT) had greater effects on wheat yields than on maize yields. First, maize is less sensitive to a compacted subsoil than wheat because of its shallow root system (and the ample supply of irrigation water and fertilizer N and P). For example, Zhou et al. (2008) found that 75% of maize roots and 45% of wheat roots were in the topsoil. They also found that winter wheat was able to use, on average, more subsoil nitrogen than summer maize. Second, maize was planted during the hot summer season and wheat during the cold winter season; as a consequence, soil temperature was not a limiting growth factor for maize. Third, the mineralization of organically bound nutrients was enhanced during the warm and humid summer season, thus alleviating any shortage of nutrients under NT conditions. Gross N mineralization is strongly related to temperature, and the difference between NT and CT was weakened in the maize season (Dong et al., 2012). Hence, there were no shortages of available nutrients in the NT treatment during the maize growing season.

4.4.3 Carbon stock and sequestration rate

The sequestration of SOC in the 0–30 cm layer was larger in the CT treatment than in the NT and RT treatments at the end of the experiment (Fig. 4.4). This contrasted with the results reported by Powlson et al. (2014) and Corbeels (2016), indicating that NT leads to a higher SOC stock than CT. Indeed, SOC stocks were larger in NT initially, but the sequestration of SOC slowed down in the NT treatment compared to the CT treatment. Corbeels (2016) observed that SOC stocks were higher in NT than in CT treatments in the Cerrado of Brazil for the first 11 to 14 years, but that the differences between NT and CT in SOC stocks were negligible thereafter. A meta-analysis by West and Post (2002) revealed that soil C sequestration lasted for approximately 20 years following the adoption of NT. In the current study, enhanced SOC sequestration under NT lasted only for a relatively short period. We speculate that the short duration of the enhanced SOC sequestration in the NT treatments may be related to the relatively large amounts of biomass returned to the soil in our double cropping system. There was essentially no increase in SOC content in the 0–5 cm soil after 2010 (following 8 years of NT adoption), indicating that a new steady state was attained, thus limiting the soil’s capacity to accumulate more SOC in the soil surface layers.

The differences among tillage treatments in SOC sequestration likely resulted from the differences between treatments in C input, decomposition rates, and physical protection of

C in soil. Ogle et al. (2012) suggested that when C inputs declined by more than 15% following NT, C stocks would also decline. The average annual C input from aboveground crop residues was slightly higher in the CT treatment than in the RT and NT treatments, but the differences were not statistically significant (Table 4.2). Interestingly, the total C stock also increased in the 0–30 cm soil layer of the CK treatment; the total SOC stock in the CK treatment was only slightly lower than those in the RT and NT treatments, despite the removal of the maize straw in the CK treatment (Fig. 4.4). These results indicate that the removal of the maize straw had only a relatively small effect on the SOC stock in the end.

Tillage may destroy soil aggregates, thereby enhancing the decomposition of organic material by microorganisms. Tillage also incorporates crop residues in the soil and partially in the subsoil, and may facilitate the downward growth of crop roots into the subsoil. This may enhance SOC sequestration in the subsoil because the rate of decomposition of organic matter is lower in the subsoil than in the topsoil due to a lower aeration and temperature.

4.5 Conclusions

This study evaluated the changes in crop yields, and in soil carbon and nutrients stocks in a winter wheat–summer maize double cropping system, with four different tillage practices imposed after maize harvests over a 17-year period. The average winter wheat yields were 18% lower under no tillage (NT) and 6% lower under reduced tillage (RT) than under conventional moldboard plowing (CT) during 2005 to 2018. Initially, NT and RT treatments rapidly increased the content of SOC in the soil surface layers, but after 17 years of SOC content was higher under the CT treatment than the NT and RT treatments. Therefore, no tillage and reduced tillage decreased both wheat yields and soil C sequestration over time. Hence, our hypotheses were both rejected. Tillage treatments did not significantly affect maize yields.

Tillage treatments influenced the distributions with the depth of available N, P and K. The AP/AN ratio in the 0–5 cm soil layer was relatively high at NT and RT treatments and low at CT and CK treatments. The AK/AP ratio was relatively high at NT and RT treatments and relatively low at CK treatments. These differential accumulations of available soil nutrients, together with a relatively high bulk density of the subsoil, may affect the nutrition of crops in the long-term, and may contribute to the relatively low winter wheat yield in the NT treatment in the double cropping system. Therefore, the dynamics of soil nutrients in different soil layers must be considered in studies evaluating the effects of tillage on soil carbon sequestration and crop yield under different regional climatic conditions.

Acknowledgements:
This research was funded by National Key Research and Development Program of China (2021YFD190100202) and Hebei Key R&D Initiative Project (20326422D).

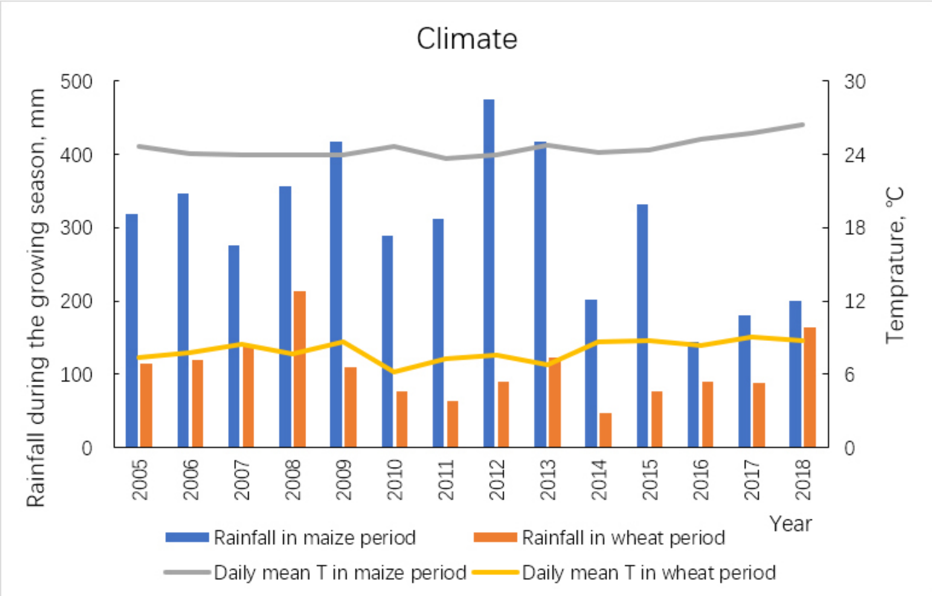


Fig. S4.1 *Average daily temperature (℃) and total precipitation (mm) during the winter wheat and summer maize growing seasons for the period 2005 to 2018.*

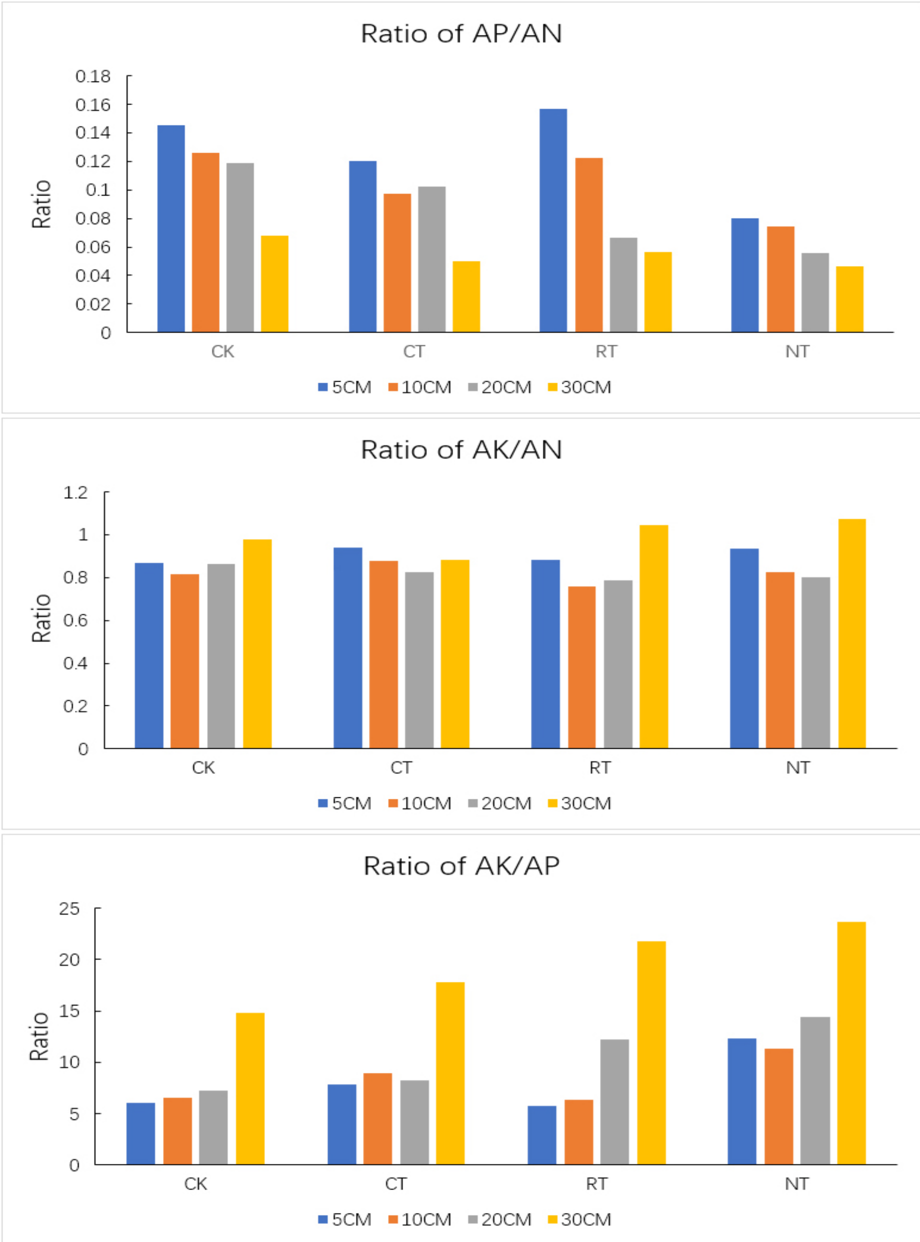


Fig. S4.2 *Ratios (wt/wt) of available P (AP) and available N (AN) (a), available K (AK) and AP (b), and of AK and AN (c) in four soil layers (0-5, 5-10, 10-20 and 20-30 cm) and four tillage treatments (means of the years 2014, 2016 and 2018)*

5. A bore-hole method for remediating compacted subsoils increased maize yield - prototype field tests

Soil compaction in agriculture is a serious threat for soil functioning. Various methods have been developed and tested during last decades to prevent soil compaction, and to remediate compacted subsoils through deep ploughing or subsoiling. These remediation measures can be effective, but are costly and may have negative side-effects. The objective of our study was to examine a prototype precision bore-hole method for row crops growing on soils with compacted subsoils. Factorial field tests were conducted on sand soil with an over-compacted subsoil below 35cm in Odiliapeel (Netherlands) and on sandy loam with over-compacted layers at 15 to 30 cm in Luancheng (China), with maize and sorghum as test crops. Treatments included bore-holes with different diameter (range 6 -10 cm) and depth (30 and 60 cm), without and with manure additions to the loosened soil used to re-fill the bore-holes. Seeds of maize and sorghum were placed above the locations of the bore-holes.

The bore-hole method was effective in enhancing maize yields by ~30% in the two field experiments in Luancheng and in one treatment in Odiliapeel. The shallow depth of the compacted soil layer likely contributed to the relatively large yield effects of the bore-hole treatments in Luancheng. No clear effects were found for differences in bore-hole diameter and bore-hole depth. We observed that roots grew preferentially in the bore-holes, but we did not find statistically significant differences in root weight between treatments for depths of 0-20, 20-40 and 40-60 cm.

Evidently, the bore-hole method was effective in enhancing the yield of maize grown on compacted subsoils, but further tests are needed for exploring the potentials of the prototype method in practice and for a better understanding of the cause-effect relationships.

Based on:
Peipei Yang, Wenxu Dong, Jan van den Akker, Oene Oenema (submitted). A bore-hole method for remediating compacted subsoils increased maize yield - prototype field tests

5.1 Introduction

Soil compaction in agriculture is a serious concern, since it affects the physics of the soil (e.g., bulk density, soil porosity, soil strength), and thereby the functioning of the soil (Batey, 2009; Nawaz et al., 2013). Over-compaction of soil may lead to decreases in crop yield and soil biodiversity, ponding water, and increases in runoff and emissions of nitrous oxide (Alaoui et al., 2018; Bussell et al., 2021). It results in increased fuel consuming in tillage, and often in additional water and fertilizer consumption, to make up the yield loss (Aridhee et al., 2020; Obour and Ugarte, 2021; Wu et al., 2022). Compaction of the subsoil is especially a concern, because it is not easily visible and/or recognized, and difficult to remediate. As a result, the effects may persists for decades (Chamen et al., 2015). Soil compaction is mostly attributed to high axle loads in mechanized agriculture (e.g., (Keller et al., 2019a; Schjonning et al., 2015)) to improper field management (Chen et al., 2022), but there are also natural and/or geo-genetic causes of over-compacted soil layers (Laker and Nortjé, 2020).

Early estimates indicate that about 68 million ha of agricultural land in the world has been affected by soil compaction (Oldeman, 1991), but these estimates are uncertain, because of lack of monitoring and lack of uniform and universal methods and criteria for assessing over-compacted soils. Both experimental measurements (e.g. (Lebert et al., 2007)) and modelling approaches (e.g., (Schjonning et al., 2015)) have been proposed. By using a statistical modelling approach, Brus and Van Den Akker (2018a) estimated that about 43% of the subsoils in the Netherlands are over-compacted.

Measures to address soil compaction are commonly categorized in three groups, i.e., (i) prevention measures, aiming at avoiding and preventing soil compaction; (ii) remediation measures, aiming at ameliorating compacted soil; and (iii) alleviation measures, aiming at neutralizing the negative effects of compacted soil (Yang et al., 2022). Evidently, preventive measure address situations where soils have not yet been (seriously) over compacted, but where soils compaction looms through high axle loads, trampling animals and/or improper soil cultivation. Preventive measures have to be prioritized (Schjonning et al., 2015). Remediation and alleviation measures address situations where the soils have been over-compacted already, either naturally or human-induced. Remediation measures break-up the compacted (sub)soil layers through subsoiling and deep ploughing (Bennie and Botha, 1986). The effects of these measures is on average positive but variable and costly, while the effects decrease over time (Peralta et al., 2021; Schneider et al., 2017; Yang et al., 2022). Also, re-compaction looms if soil management is not adjusted. Alleviation measures also address situations with compacted subsoils; these measures aim at neutralizing the negative impacts of soil compaction through (increased/improved) fertilization, irrigation and/or drainage, but do not address the cause of the negative impacts. Evidently, all types of measures may be needed in the end, depening on site-specific conditions (Yang et al., 2022).

Compacted subsoil often requires remediation for proper soil functioning and diminishing the aforementioned negative impacts. Deep ploughing and subsoiling are common measures for compacted subsoil remediation, but have drawbacks. They require large power and large amounts of energy, and the effects do not last for long (Schneider et al., 2017). Deep ploughing reverses soil horizons, thereby burying fertile topsoil while the 'open soil condition' is vulnerable to re-compaction by subsequent machinery traffic and grazing animals (Spoor, 2006). Subsoiling is less destructive for the soil profile than deep ploughing, depending also on the depth, width and shape of the shanks and blades, and the frequency of subsoiling (Raper and Bergtold, 2007). The latter authors suggested to use controlled traffic concepts to ensure alignment of plant rows and subsoiled zones, and to further optimize the shape and size of the shanks and blades, to save draft and fuel. They also indicated that two passes of a tractor in the subsoiled area will cause the soil to return to its previous state prior to subsoiling. In a long-term field experiment in China, Yang et al. (2021) observed that subsoiling combined with applying organic manure gave better soil functioning than subsoiling without organic manure, or compared to organic manure application without subsoiling. Rather similar results were obtained by Leskiw et al. (2012) in a field experiment in Canada. Recently, Makange et al. (2021) improved our understanding of the mechanism and the practice of precision subsoiling further through a combination of simulation modelling, sensors and experimental testing. This increased understanding contributes to lowering draft and fuel consumption by subsoiling and to greater endurance of the effects.

Evidently, there is a need for greater precision and lowering the cost and negative side-effects of ameliorating subsoil compaction. Greater precision refers to ameliorating subsoil compaction to where it is mostly needed, which depends of course on the soil conditions, crop type and planting structure. Lowering the cost and negative side-effects also depends on soil conditions and on where and how the amelioration is conducted. Thus precision subsoiling seems to be preferred above deep ploughing as measure to ameliorate subsoil compaction. A possible further step is to ameliorate subsoil compaction only below plants, growing in rows, especially when yield loss is the main impact of over-compacted soil. This notion led to the idea to develop and test a 'precision bore-hole method', whereby amelioration of the soil is localized in bore-holes, positioned below the plants. The objectives of this ' precision bore-hole method' are (i) to locally ameliorate over-compacted subsoils for growing crops, (ii) to lower the demand for power and energy for ameliorating over-compacted subsoil; (iii) to maintain the original soil profile where needed and possible, so as to minimize the risk of soil instability, and (iv) to allow adding soil amendments to the soil in the bore holes. Evidently, this method is most applicable to row crops, which growth and development of roots are hampered by subsoil compaction, and to fields where bore-holes through compacted soil may increase infiltration and drainage.

The objective of the study reported here was to test the effectiveness of proto-types of a precision bore-hole method on root growth and crop yield in soils with compacted subsoil. A series of prototype tests were conducted to find out the optimal depth and diameter of the bore-holes, and the effects of adding manure to the soil in the bore-holes. Maize and sorghum were selected as test crops, because maize and sorghum have different sensitiveness to soil compaction (Altuntas et al., 2005; Awadhwal and Thierstein, 1985). Experiments were conducted in The Netherlands (where contractors often use large machines with high axle loads) and China (with small-holder agriculture and small machines). We hypothesis that: (i) maize will profit more from the boreholes than sorghum, because maize roots will preferentially growth in the loosened soil in the bore-holes below the planting hole, and thereby increase crop yields, (ii) the effectiveness of the boreholes depend on their depths and diameters, and (iii) amending the soil with manure in bore holes favors root growth and crop yield.

5.2 Materials and methods

5.2.1 Site description

Filed experiment were conducted in Odiliapeel (51°40’N, 5°44’E, mean elevation 22 m), South-East of The Netherlands, and Luancheng (37°53’N, 114°41’E, mean elevation 50 m) in the North China Plan (NCP), China. Climate in The Netherlands is temperate maritime with mild winters and cool summers. The annual mean temperature is 10.8℃ and the mean annual precipitation 832 mm. North China Plain has a subtropical monsoon climate, with cold and dry winters and warm and humid summer months. The annual mean temperature is 12°C and the annual mean precipitation 530 mm in Luancheng.

Odiliapeel has a sandy soil with 1% clay and 7-9% silt (Table 5.1), which is vulnerable to compaction. The land has been intensively cultivated (potatoes, vegetables, silage maize) and manured in the past, and is commonly irrigated during dry-spells. Carrots were grown in 2016, before which a relatively deep tillage (~35 cm) was applied. At the start of the field experiment, soil bulk density was 1.48 g/cm^3 in the topsoil and 1.68 g/cm^3 in the subsoil.

The Luancheng Agroecosystem Experimental Station is a main research facility of the Chinese Academy of Sciences, and is in the piedmont region of the Taihang Mountains, at the fringe of the NCP. Soils in Luancheng have sandy loam texture, with a clay content of 17-18% and silt content of 58-60% (Table 5.1). The common, double cropping system is winter wheat – summer maize, with flood irrigation in the NCP. Shallow rotary tillage (0-10 cm) is conducted after maize harvest and no-tillage after winter wheat harvest. Soils have a relative high soil bulk density at depth >15 cm.

Table 5.1 *Background soil characters in each experimental site*

Site	Soil layer	BD g/cm^3	Clay content %	Silt content %	SOM content %
Odiliapeel	Topsoil (15-25cm)	1.48	1	9	2.51
	Upper subsoil (30-50cm)	1.68	1	7	0.48
	Lower subsoil (50-70cm)	1.69	1	7	0.40
Luancheng	Upper subsoil (15-20cm)	1.62	17	58	2.09
	Lower subsoil (25-35cm)	1.66	18	60	0.99

5.2.2 Field experiments in Odiliapeel

Two field experiments were conducted, each with 12 treatments, including 3 bore-hole treatments, 2 manure treatments (with and without manure application) and 2 crops (silage maize and sorghum). The planting density was 9 plants/m^2 for both maize and sorghum, equivalent to 90,000/ha. The area of each plot was 1m*1m

In 2017, bore-hole treatments included (i) no bore-holes (C0, control treatment), (ii) 5 holes (Ø 1 cm; depth 60 cm) within a circle (Ø 30 cm) around each plant (C1), and (iii) 1 bore-hole (Ø 6 cm; depth 60 cm) per plant (C6). Treatments were carried out in triplicate. In 2018, bore-hole treatments included (i) no bore-hole (C0), (ii) 1 bore-hole (Ø 6 cm, depth 60 cm) per plant (C6), and (iii) 1 bore-hole (Ø 9 cm, depth 60 cm) per plant (C9). Treatments were carried out in quadruple.

The five bore-holes 'bore-holes' of C1 (Ø 1 cm; depth 60 cm) per planting hole were made by the stick of a hand penetrometer, and were not treated further. The bore-holes of the

C6 and C9 treatments were made by hand augers; here bore holes were filled again with loosened soil (separately for 0-30 cm and 30-60 cm layers). In the manure treatments (indicated by "+"), dried chicken manure was either surface applied and incorporated in the top 5 cm of the soil (C0 and C1 treatments) or mixed with the soil 0-30 cm from the bore holes. Manure was applied at 110 kg N ha^{-1}. The composition of the manure is presented in Table S5.1)

One month after sowing, the germination rate was recorded. Weeding was done when considered necessary (once in 2 to 6 weeks, depending on rainfall and the crop coverage of the soil). Irrigation was not applied, so as not to alleviate the effects of soil compaction.

At harvest, whole plants were harvested and threshed manually. The grain yield and biomass yield were dried and weighted respectively. After harvest, soil-root columns were taken to examine the root profiles in selected treatments in triplicate; soil columns (35 cm wide, 10 cm thick and 60 cm deep) below the center plants were taken from excavated soil pits, using a 35x60 cm large pinboard with 10 cm long nails (Schuurman and Goedewaagen, 1971). Soil columns were transported to the laboratory, and the soil was gently rinsed from the roots on the same day as the soil columns had been taken. Root profiles were photographed, and the root mass from 0-20 cm, 20-40 cm and >40 cm were dried at 65°C and the dry weight recorded. Dried roots were incinerated at 300°C and the ash weights were recorded.

During the growing periods, daily mean temperature was 17.2°C in 2017 and 19.3°C in 2018. Total precipitation was 325 mm in 2017 and 170 mm in 2018 (Fig. 5.1). Crops suffered from drought in both years, especially in 2018. After harvest, soil penetration resistance (PR) was measured around the roots in each plot in triplicate and the results were averaged per depth.

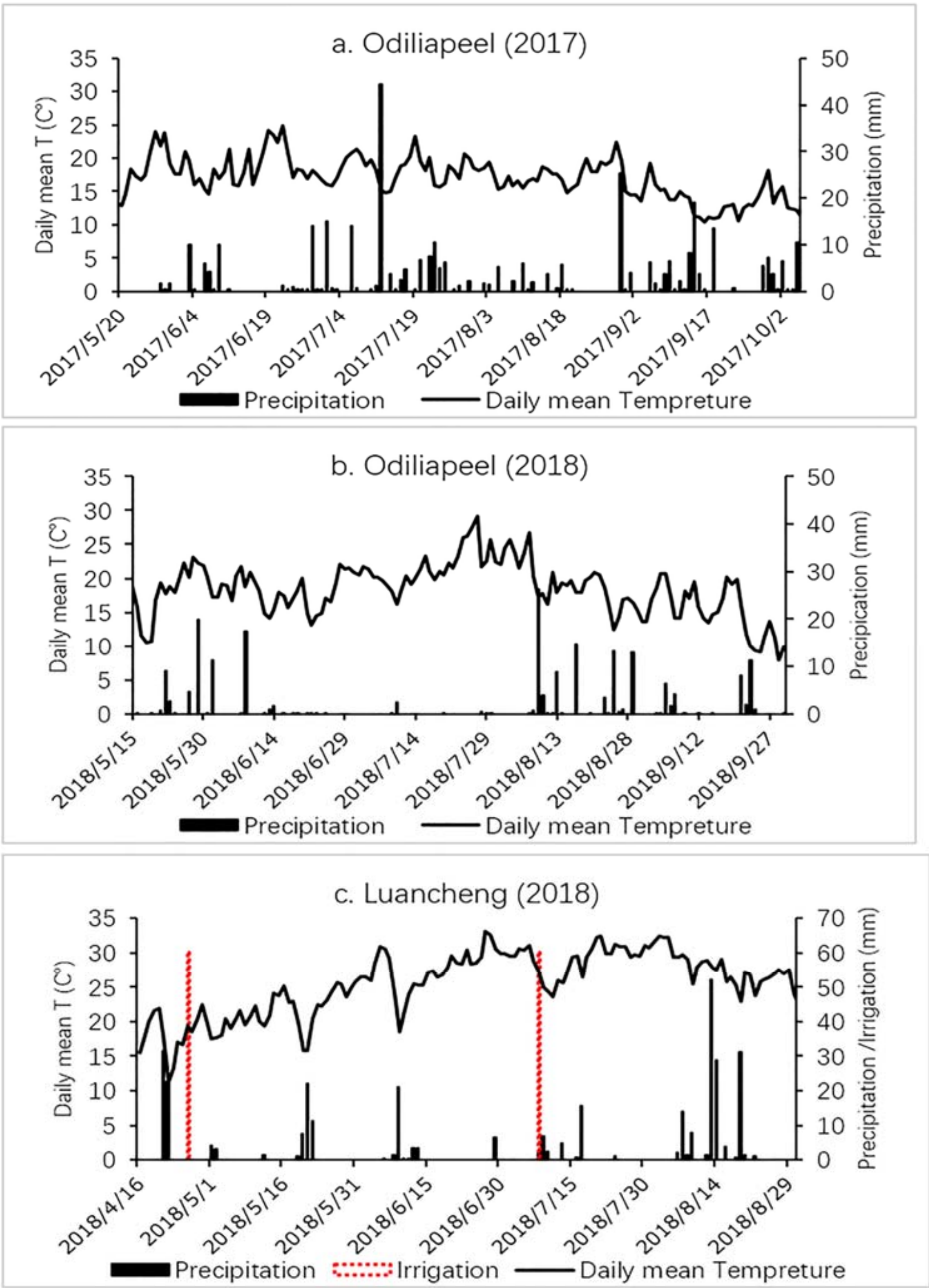


Fig. 5.1 *Daily mean temperature and precipitation during the growing seasons in Odiliapeel in 2017 (a) and*

2018 (b), and in Luancheng in 2018 (c).

5.2.3 Field experiments in Luancheng

Two experiments were conducted, in Luancheng North and Luancheng South. It was planned to irrigate the North field (as is common practice) and the South field not (so as not to alleviate the effects of soil compaction), but because of the dry conditions at planting both fields were irrigated and ultimately had the same design and management. Only maize was planted, and the planting density was 90,000/ha, equivalent to Odiliapeel, but higher than the Luancheng local practice (55,000/ha). The area of each plot was 1.34m*1.34m, i.e., 16 plants per plot.

The experiments had 10 treatments, i.e., 5 soil bore-hole treatments combined with 2 manure treatments (without and with manure application). Bore-hole treatments included (i) no bore-holes (C0, control treatment), (ii) 1 bore-hole (Ø 7 cm, depth 30 cm) per plant C7/30, (iii) 1 bore hole (Ø 7 cm, depth 60 cm) per plant (C7/60), (iv) 1 bore hole (Ø 10 cm, depth 30 cm) per plant (C10/30) and (v) 1 bore-hole (Ø 10 cm, depth 60 cm) per plant (C10/60), in triplicate. The bore-holes were made by hand augers, and bore holes were filled again with loosened soil (separately for 0-30 cm and 30-60 cm layers). In the manure treatments (indicated by "+"), dried pig manure was either surface applied and incorporated in the top 5 cm of the soil (C0 treatment) or mixed with the soil 0-30 cm from the bore holes. Manure was applied at 110 kg N ha^{-1}. The composition of the manure is presented in Table S5.1).

Following planting, 60 mm of irrigation was given on Apr 26 and again on July 8 respectively, which is common practice in the region. But the maize still suffered from drought due to high temperature and strong transpiration (Fig. 5.1). Manual weeding was conducted when deemed necessary.

Whole maize plants were harvested and threshed manually. Biomass and grain were dried at 65°C and weighted. Root profiles were examined in the South site, using the same procedure as in Odiliapeel. After harvest, soil penetration resistance (PR) was measured in each plot in triplicate and the results were averaged per depth.

5.2.4 Statistical analysis

Statistical analyses were performed using R Software (version 4.0.3, (RCoreTeam, 2013)). The significance of between-treatment differences in grain yield, root weight, and soil penetration resistance (PR) were analyzed using analysis of variance (one-way ANOVA). The Least Significant Difference (LSD) test was used for multiple comparisons between means of treatments. Functions of avo() and LST.test() were applied in the calculations. The differences were only considered significant when $P < 0.05$. Figures and tables were performed by Microsoft Office 2010 and R studio (version 1.1.463).

5.3 Results

5.3.1 Grain and biomass yields

Within-treatment variability in grain yields was high in Odiliapeel, and differences between mean yields of bore-hole treatment were not statistically significant, apart from the maize in 2018; maize grain yields of C9 were higher than those of C0 (Fig 5.2a). The large within-treatment variability was attributed to drought (including a poor germination) and to the small plots. Mean maize grain yields (6 to 10 Mg/ha/yr) were relatively low compared to national average maize grain yields (8 to 14 Mg/ha/yr). Mean sorghum grain yields (4 to 6 Mg/ha/yr) were also low (Fig 5.2b); sorghum was introduced only recently in The Netherlands and there are no robust yield statistics yet. Manure addition had no effect on grain and biomass yields in Odiliapeel, and thus yields were averaged over bore-hole treatments (Fig. S5.2).

There were significant differences between bore-hole treatments in maize grain yields in Luancheng, in both fields (Fig. 5.2c). The widest bore-holes (treatments C10) tended to give the highest yields ($P<0.05$, Fig. 5.2c); differences in mean grain yield were 1 to 2 Mg/ha/yr. There were no clear differences between a bore-hole depth of 30 cm and 60 cm, which was likely related to the shallow depth of the over-compacted soil. Within-treatment variability in grain yields was smaller in Luancheng than in Odiliapeel, likely because of the somewhat larger plots and the influence of irrigation.

Differences between treatments in biomass yields were rather similar to the differences in grain yields (Fig. 5.3). Effects of the bore-hole treatments were small in Odiliapeel and significant in Luancheng South (but not in Luancheng North). The mean biomass yields of maize and sorghum in Odiliapeel were much lower in 2018 than in 2017 (Fig 5.3a, 5.3b), while mean grain yields did not differ much between 2017 and 2018 (Fig 5.2a, 5.2b). This apparent anomaly was attributed to the use of different crop varieties, and to the period of drought stress, which was different between 2017 and 2018 (Fig. 5.1). There were no differences between manure treatments in biomass yield (Fig. S5.3).

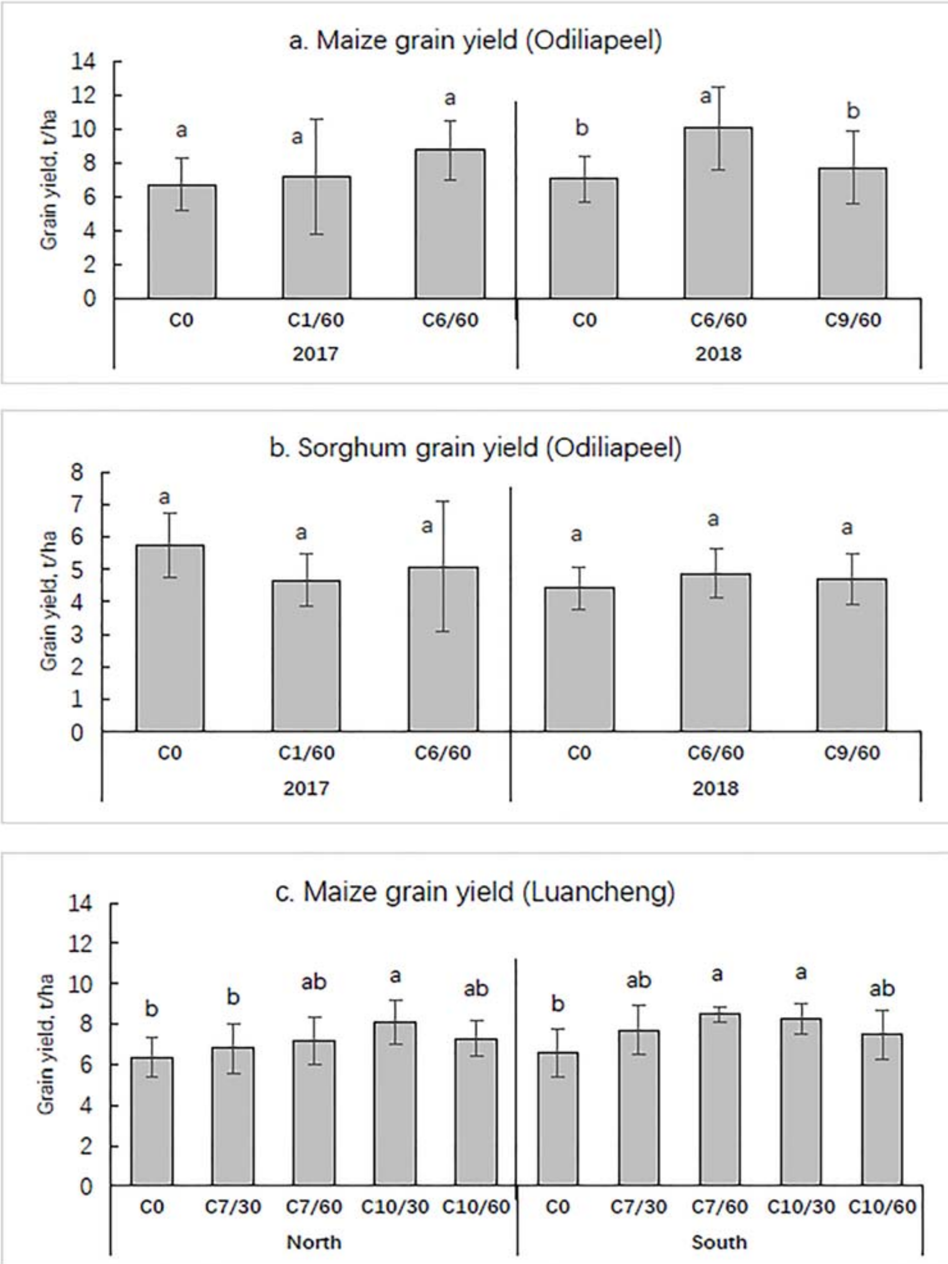


Fig. 5.2 *Mean grain yields of maize and sorghum, as affected by bore-hole treatments in Odiliapeel (a, b) and in Luancheng (c). Mean results of the bore-hole treatments (including manure and no manure treatments). Error bars indicate standard deviations; treatments sharing the same letters are not significantly different at P < 0.05 level according to the LSD test.*

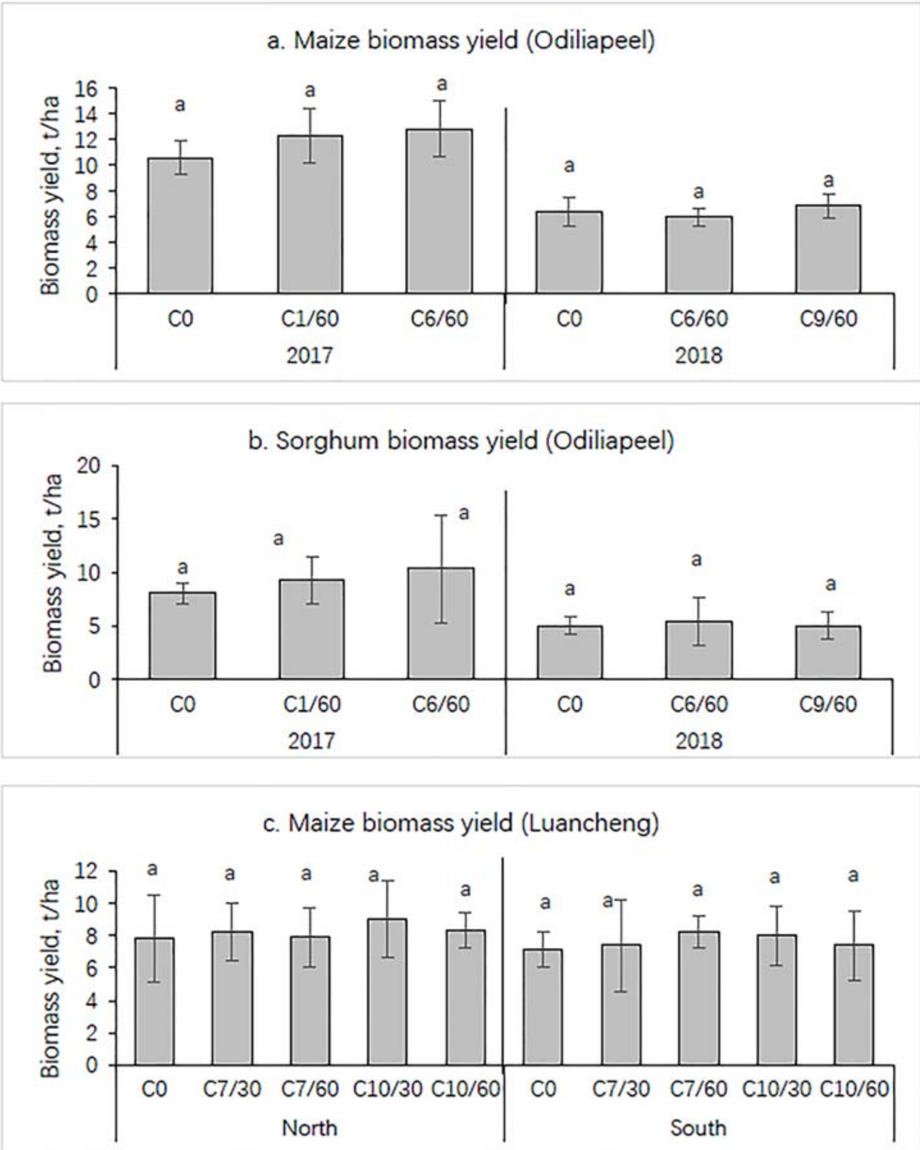


Fig. 5.3 *Mean aboveground biomass yields of silage maize and sorghum, as affected by the bore-hole treatments and manure application in Odiliapeel (a, b) and in Luancheng in 2018 (c). Mean results of the bore hole treatments, including the manure and no manure treatments. Error bars indicate standard deviations; treatments sharing the same letters are not significantly different at P < 0.05 level according to the LSD test.*

5.3.2 Root distributions and weights

More than 80% of the total root weight was found in the upper 20 cm in Odiliapeel (Fig 5.4a) and Luancheng (Fig. 5.4c). Sorghum plants had a slightly smaller proportion of roots in the topsoil than maize; sorghum had relatively more roots in the soil layers 20 to 40 cm and 40 to 60 cm than maize (Fig. 5.4b). There were no statistical differences between treatments in total root weight of both maize and sorghum in Odiliapeel. However, total root weight was significantly higher in treatments with bore holes than in the treatment without bore holes in Luancheng South (Fig. 5.4c), notably in the top 0-20 cm. The increase in root weight in the top 20 cm of the soil reflects that the soil was compacted at shallow depth (Table 5.1), which is in line with the shallow rotary tillage (0-10 cm). The total root mass in the subsoil did not increase in the bore-hole treatments, which supports the finding that 60 cm deep bore-holes did not gave higher maize yields than 30 cm deep bore-holes in Luanchuang (Figs 5.2c, 5.3c). Root distributions with depth and total root weight were not affected by manure.

Visual observations of the root profiles revealed that roots of maize and sorghum in the subsoil preferentially followed bore-holes (e.g. Fig. 5.1), suggesting that roots could easily penetrate the loosened subsoil in the bore-holes to a depth of 60 cm. This concentration of maize roots and to a lesser extent of sorghum roots did not lead to statistically significant increases in root weight in the 20 to 40 cm soil layers (Fig 5.3a, 5.3b). However, we did not quantify the root length distribution, which commonly is a better indicator for root activity (de Moraes et al., 2020).

5.3.3 Soil penetration resistance

Soil penetration resistance was measured after the harvest of the crops. Tests were conducted near the original positions of the maize and sorghum plants. Results indicate that bore-hole treatments had lower penetration resistance than the control treatments in Odiliapeel in both 2017 and 2018 (Fig. 5.5a, 5.5b). In 2017, penetration resistance increased strongly between depth of 40 and 60 cm (Fig. 5.5a). In 2018, penetration resistance at shallower depth than in 2017 in the control treatments, mainly because of differences in soil moisture content. However, the increases with depth were much lower in the bore-hole treatments than in the control treatments (Fig. 5.5b).

Mean penetration resistance was lower in the sandy loam soil of Luancheng than in the sandy soil of Odiliapeel, especially in the subsoil. Further, penetration resistance values were significantly lower in the bore-hole treatments than in the control treatment in

Luancheng North and South (Fig. 5.5c). Treatments with wide (Ø 10 cm) and deep (60 cm) bore-holes had the lowest penetration resistance, as expected. Differences were statistically significant below a depth of about 10-15 cm.

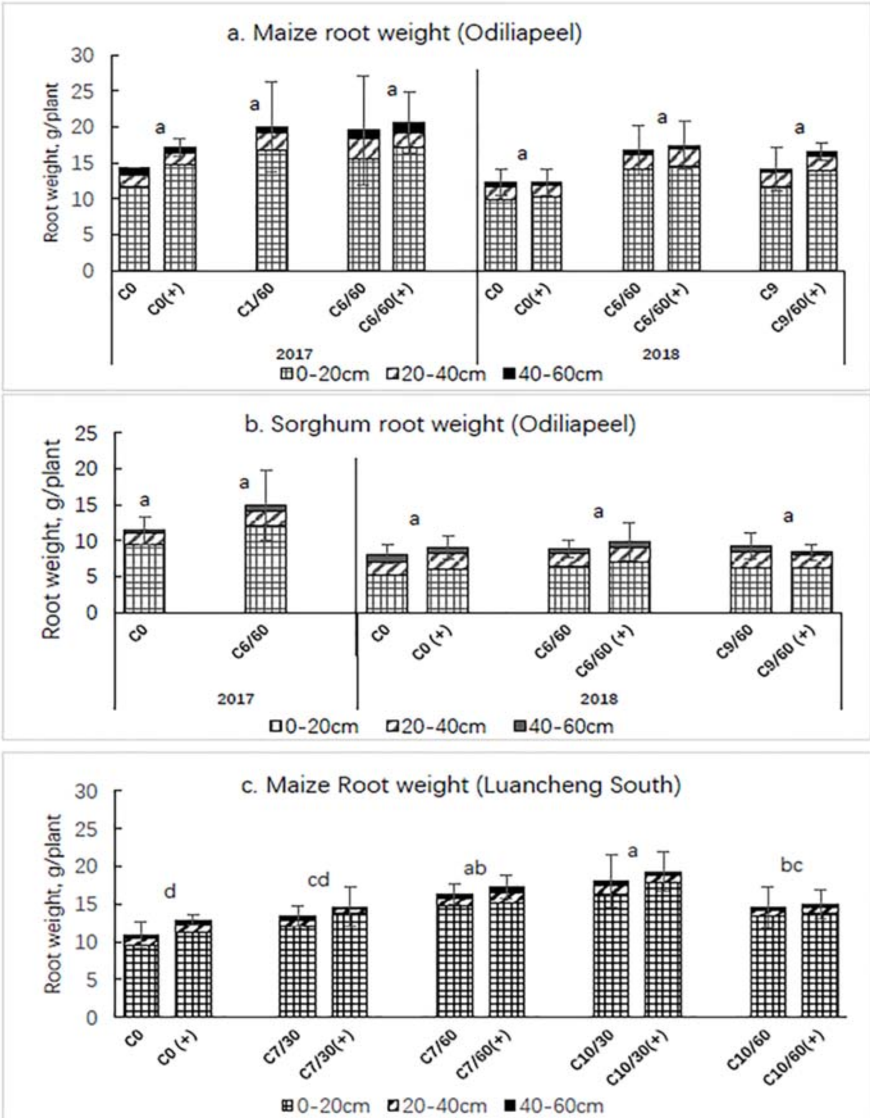


Fig. 5.4 *Dry root weight per plant (means ± s.d.) as function of bore-hole treatment in Odiliapeel (a, maize; b, sorghum) and in Luancheng South site (c, maize). Error bars indicate standard deviations of total root dry weight of each plant. Treatments with the same letter are not significantly different at P < 0.05. Means of the bore-hole treatment include the manure and no manure treatments.*

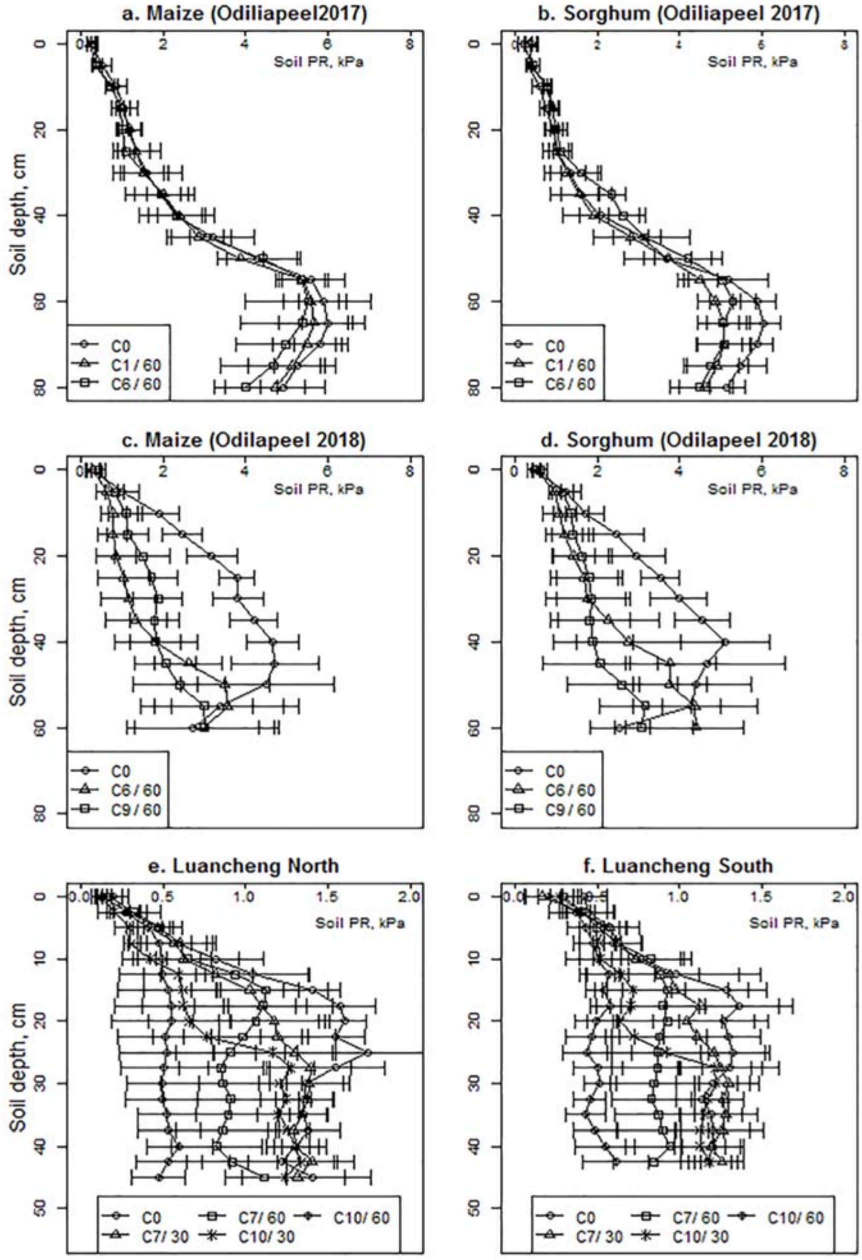


Fig. 5.5 *Soil penetration resistance in kPa (means ± s.d., n=3) at different depth as function of bore-hole treatment at harvest time in Odiliapeel 2017 (a, b), 2018 (c, d), and Luancheng north site (e), Luancheng south site (f). Results of bore-hole treatments were averaged over manure treatments.*

5.4 Discussion

5.4.1 Effects of bore-hole diameter and depth

The sandy soil in Odiliapeel and the sandy loam in Luancheng have high to very high susceptibility to compaction, according to the texture-packing density classification of (Spoor et al., 2003). Both soils were rather homogenous with depth in soil texture, but the compacted layer was at shallow depth in Luancheng (10-30 cm), due to shallow rotary cultivation and flood irrigation, and relatively deep (>35 cm) in Odiliapeel, due to relatively deep soil cultivation. Such differences will affect the responses of the crop to the compacted soil layers, as well as to the bore-hole treatments. We tested only one bore-hole depth (0-60 cm) in Odiliapeel and two in Luancheng (0-30 and 0-60 cm), combined with two diameters (6 and 9 cm in Odiliapeel, and 7 and 10 cm in Luancheng; augers slightly differed in size between Odiliapeel and Luancheng because of different local practices). We tested also very narrow (Ø 1 cm) 'bore-holes' (5 holes within a circle (Ø 30 cm) around each plant in Odiliapeel in 2017. However, there was no yield response (Fig. 5.2a, 5.2b), and observations on root distribution profiles revealed that roots did not preferentially growth in the holes (not shown). Thus, this treatment was not examined further. In contrast, one large bore-hole (Ø 6 cm) per plant increased maize yield in 2018 significantly, and root distribution profiles revealed that roots did growth preferentially in these holes (Fig. S5.1), suggesting that the bore-hole remediation practice was effective. However, a larger bore-hole diameter (Ø 9 cm) did not increase maize and sorghum yields in Odiliapeel (Fig 5.2a,5.2b).

Bore-holes increased maize grain yields in both experiments in Luancheng (Fig. 5.2c). The mean increase in grain yield was nearly 2 Mg/ha in both years, equivalent to an increase of nearly 30% relative to the control treatment. This increase is larger than the mean increases in yield (6 to 10%) following deep ploughing or subsoiling (Schneider et al., 2017; Yang et al., 2022). There was no clear effect of bore-hole diameter (7 versus 10 cm), and bore-hole depth (30 versus 60 cm), although the root biomass tended to be larger in the treatments with the wider diameter, i.e., 10 cm (Fig. 5.5c). The lack of a difference between bore-hole depths of 30 cm and 60 cm was not a surprise, as the compacted soil layer was at 10-30 cm in Luancheng, and most of the root biomass weight (≥90%) was in the upper 20 cm (Fig. 5.5c). Thus remediating the compacted subsoil in Luancheng through bore-holes appears to be an effective method to significantly increase grain yields. The mechanism of the yield-enhancing effect of the bore-hole treatments is likely related to better and deeper root growth, especially during the early stages of plant development, and to greater access to soil water and nutrients. It should be noted that the crops were well-fertilized and irrigated, which will have alleviated the effects of subsoil compaction (e.g., (Zhang et al., 2012), but yet bore-hole treatments were effective in enhancing crop yield.

Manure addition, either broadcast on the soil surface in control treatments (and in the C1 treatment), or mixed with the top 30 cm of the soil from the bore-holes, did not have a crop yield enhancing effect (Fig. S5.2), suggesting that the crops were not limited by (micro)nutrients at both field sites. Yet, manure placement in the bore-holes has the potential to increase the effectiveness and the recovery in the crop of nutrients from the applied manure (Maillard and Angers, 2014), and at the same time guide plant roots through the bore-holes.

5.4.2 Prototyping and testing a protype

The word 'prototype' comes from the Latin words 'proto' (original) and 'typus' (model). A prototype is an early idea, concept or technique. Prototypes are being developed, tested and used in almost all sectors of society, including agriculture, construction, art, and simulation modeling. The idea of making and testing prototypes is centuries old, but the method of prototyping has become more formalized during the second half of the 20th century. For example, Vereijken (1997) described a formal method for prototyping and testing integrated and ecologically more sustainable arable farms. Yet, also less planned and designed ideas emerge and are being tested and further developed, including in soil compaction research. Prototype sensors for measuring soil compaction from the viewpoint of soil mechanics were reviewed by Hemmat and Adamchuk (2008); they discussed shortcomings of the protypes and identified priorities for further development. Machada and Lancas Machado and Lancas (2016) evaluated a prototype sensor to identify compacted soil layers and to control chiseling depth; they found that mechanical chiseling at variable depths reduced fuel consumption. Protype remediation and alleviation measures for soil compaction were discussed by Spoor (2006) in terms of soil fissuring and loosening; subsoiling should create fissures in the compacted soil layer with minimal disturbance. Such fissures in compacted soil layers will increase drainage of excessive water, and may have a conducting function for plant roots. Alternatively In a vineyard of South Africa, 90cm depth of trenches were applied in 1/4 area of the field, which shifted each year, and the whole field could receive loosening every 4 years; up to 69% of grape yield increase was obtained in that study (Laker and Nortjé, 2020).

Basically, our bore-hole method is an early prototype of a method and/or technique that incorporates ideas proposed by (Makange et al., 2021; Raper and Bergtold, 2007; Spoor, 2006). The aim is to remediate over-compacted subsoils with high precision (underneath growing plants only) to enhance root growth and soil drainage, and to minimize the negative side-effects that often occur with subsoiling and deep plowing, i.e., high power and energy demands and high risk of re-compaction. Instead of creating more or less horizontal fissures with minimal disturbance, as is done with subsoiling, we created vertical bore holes in the compacted subsoil, which were refilled with loosened (and manured) soil. This practice resembles also the ideas of digging narrow (90 cm deep) trenches in vineyards in South Africa to ameliorate natural compacted subsoil; trenches were refilled with loosened and amended soil, and the grape trees planted in the amended strips gave up to 69% higher grape yields (Laker and Nortjé, 2020). However, a bore hole is from the mechanical point of view much more stable than a trench.

Bore-holes were made by hand augers, and tests were made in small plots. The total bore-hole area was ≤7% of the total surface area, which is far less than the case with deep ploughing and subsoiling. No prototype bore-hole machine was made and tested, and thus no evaluation can be made of the demands for power and energy. Yet, designing a prototype bore-hole machine may be done on the basis of the results of our bore-hole testing. We tested the prototype idea in field experiments, using maize and sorghum as test crops, and using crop yield and root growth as criteria, relative to control treatments without bore-holes. Thus, the impact of remediating over-compacted subsoil was evaluated, and not the driving forces, pressures and state indicators of soil compaction (Schjonning et al., 2015). Commonly, impact follows from a change of the state (and/or pressures and driving forces), and thus is a most important indicator as it deals with the functioning of the soil ecosystem services (Bünemann et al., 2018; Schulte et al., 2014). However, the mechanistic cause-effect relations creating the yield effects in the field experiments with our bore-hole prototype need further study.

5.4.3 Limitations of the study and outlook

The bore-hole method turned out to be effective in enhancing yield in the two field experiments in Luancheng and in one experimental treatment in Odiliapeel, indicating that the bore-hole method can be effective in ameliorating over-compacted soils. However, further tests and measurements are needed before bringing the method to practice. The needed test related to the optimal diameter and depth of the bore-holes, which likely depend on the depth of the over-compacted soil layer and crop type. The cause-effect relationship of the yield enhancing effect of the bore-hole method also requires further mechanistic underpinning through additional observations and measurements.

Next, prototype machines should be developed that are able to make bore-holes with the require diameter and depth, and at the appropriate place. Alternatively, the machine makes narrow trenches on the position of the planting rows, similar to trenches in the vineyards described by Laker and Nortjé (2020). The required investments, power, energy and time are important criteria for assessing the prototype machine. Likely, the cost increase with the depth of the bore-holes and trenches, as with deep ploughing and subsoiling (Patterson et al., 1980).

The bore-hole method has been developed for row crops, and would be most applicable for perennial crops, i.e., fruit trees and vineyards, because bore-holes (planting holes) have to be made only at planting the trees. For annual crops growing in rows, either new bore-holes have to be made each year, or precision positioning machines allow seeding above the earlier made bore-holes. Not all row crops may respond well to the bore-hole treatments; e.g. sorghum did not respond in Odiliapeel, likely because (1) a late and slow start of the germination of sorghum due to the cold temperature and initial drought (Fig. 5.1) and (2) sorghum roots mainly proliferate the upper 0-30 cm of soil intensively (Lemaire and Charrier, 1996; Singh et al., 2010); and the 35 cm thick topsoil diminished the need for deep rooting. Therefore, in soils where subsoil compaction is too difficult to remediate, sorghum could be a substitute for silage maize.

5.5 Conclusions

Literature reports indicate that there is an increasing need to prevent subsoil compaction by heavy machines and inappropriate soil cultivation, and to ameliorate over-compacted subsoils and/or alleviate the impacts of over-compacted subsoils. Ameliorating compacted subsoil by deep ploughing or subsoiling can be effective, but is associated with high cost and re-compaction looms. We tested a precision bore-hole method as prototype for ameliorating compacted subsoils planted with row crops, i.e., maize and sorghum. Bore-holes varied in diameter (6 to 10 cm) and depth (30 to 60 cm) and were re-filled with loosened soil (without or with manure amendment). Next, seeds were planted above the positions of the bore-holes. The bore-hole method was effective in enhancing maize yields by ~30% in the two field experiments in Luancheng (China) and in one experimental treatment in Odiliapeel (The Netherlands). The compacted soil layer was at 15-30 cm in Luancheng and at 30-50 cm in Odiliapeel, and this difference likely contributed to the greater effects of the bore-hole method in Luancheng. No clear differences were found for the bore-hole diameter in the range of 6 to 10 cm. Also, the yield enhancing effect was similar in treatments with 30 cm and 60 cm deep bore-holes in Luancheng. We observed that roots grew preferentially in the bore-holes, but we did not find statistically significant differences in root weight between treatments for depths of 0-20, 20-40 and 40-60 cm.

Evidently, the bore-hole method was effective in enhancing the yield of maize grown on compacted subsoils, but further tests are needed for exploring the potentials of the prototype method in practice and for a better understanding of the cause-effect relationships.

***Fig. S5.1** Maize roots of the bore-hole C6 treatment in Odiliapeel 2017, showing that roots grew preferentially in bore-holes*

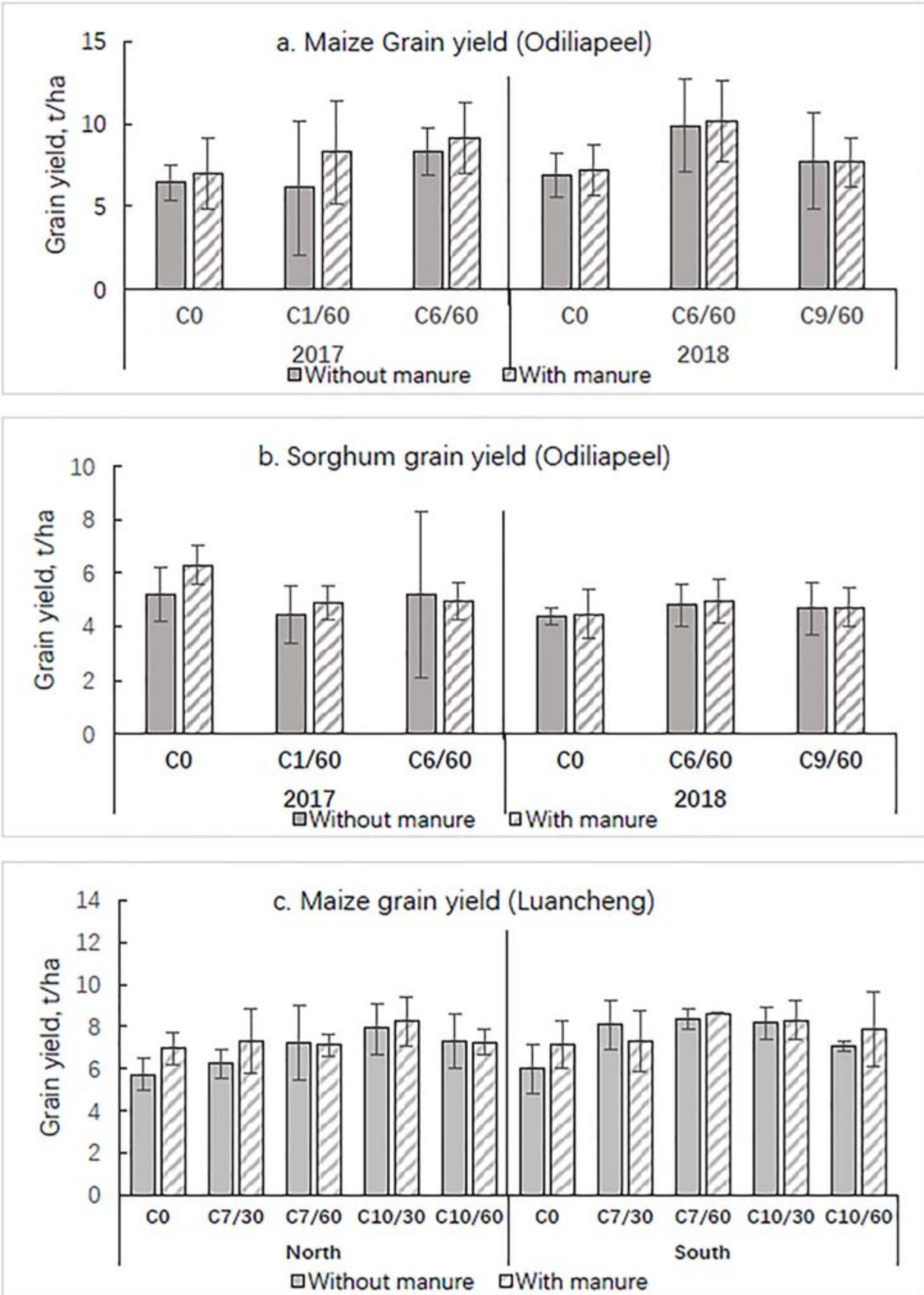


Fig. S5.2 *Results of all treatments. Mean grain yields of maize and sorghum, as affected by bore-hole treatments and manure application in Odiliapeel (a, b) and in Luancheng (c). Error bars indicate standard deviations.*

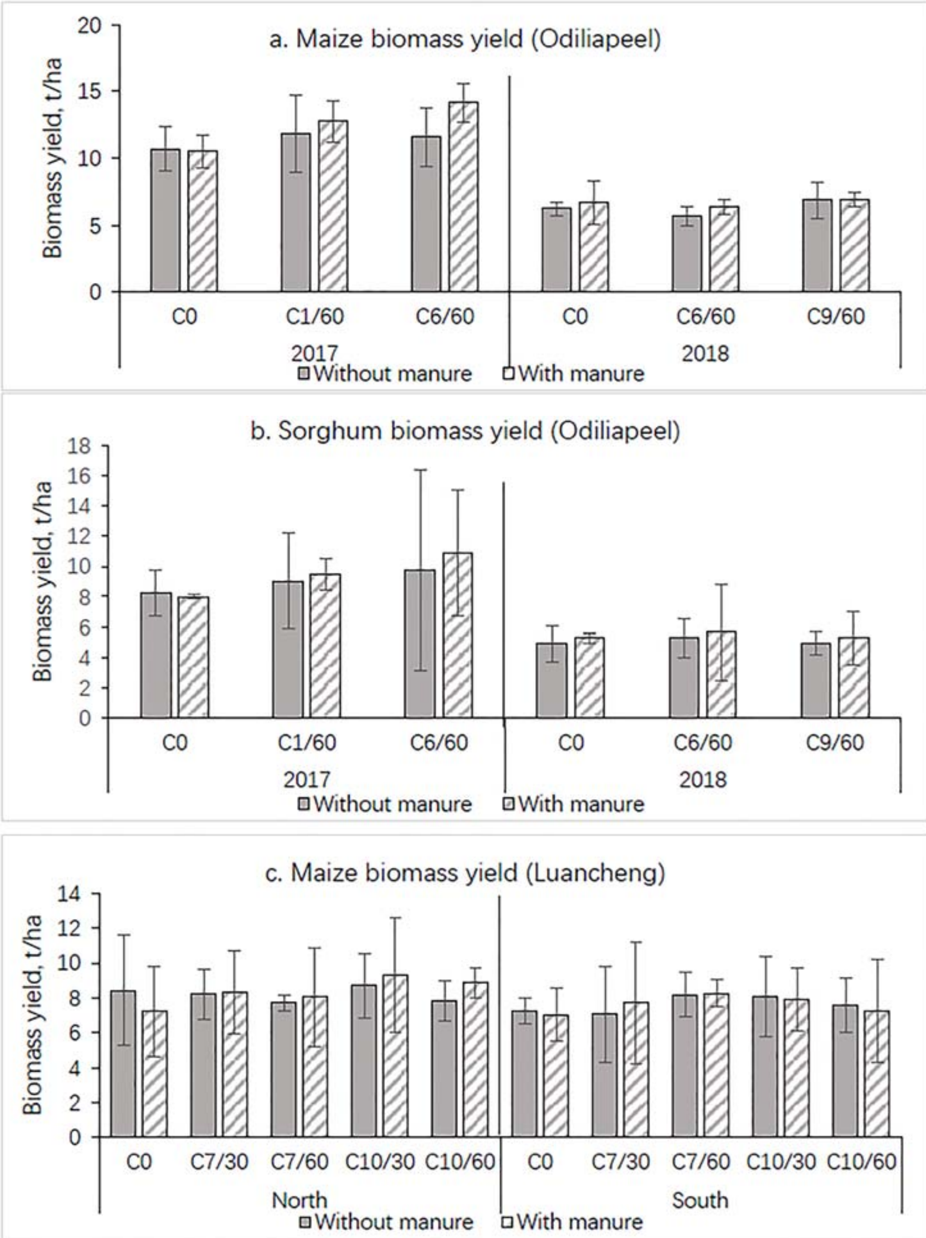


Fig. S5.3 *Results of all treatments. Mean aboveground biomass yields of silage maize and sorghum, as affected by the bore-hole treatments and manure application in Odiliapeel (a, b) and in Luancheng in 2018 (c). Error bars indicate standard deviations.*

Table S5.1 *Nutrient content (% of dry weight) of manure applied*

Site	Manufacturer	Nutrient	Content
Odiliapeel	Monterra, NL	Organic N NH_4^+- N P_2O_5 K_2O MgO	8% 3% 8% 2% 1%
Luancheng	Lvyuan, CN	Organic matter N+ P_2O_5+ K_2O	40% ≥5%

Table S5.2 *Biomass yield (Y_B), grain yield (Y_G), total root weight (W_{root}) (means±s.d.) in all 4 experiments. Different letters in the same column of each experiment indicate significant differences at p<0.05.*

Plant	Site	Year	Treatment	Y_B	Y_G	W_{root}
Maize	Idiliapeel	2017	C0	44.9±5.1 a	6.7±1.6 a	16.4±1.7
			C1/60	50.7±13.9 a	7.2±3.4 a	20±6.2
			C6/60	56.1±9.1 a	8.7±1.7 a	20.1±5.6
		2018	C0	20.2±3.5 b	7.0±1.4 b	12.3±1.7
			C6/60	24.0±3.8 a	10.0±2.4 a	17±3.1
			C9/60	21.9±2.2 ab	7.7±2.2 b	15.4±2.5
Sorghum	Idiliapeel	2017	C0	44.4±3.0 a	5.8±1.0 a	11.4±1.9 a
			C1/60	44.6±8.4 a	4.7±0.8 a	
			C6/60	49.3±11.1 a	5.1±2.0 a	14.9±4.9 a
		2018	C0	19.0±2.1 a	4.4±0.6 a	8.6±1.5 a
			C6/60	20.7±5.7 a	4.9±0.8 a	9.4±1.6 a
			C9/60	19.5±3.9 a	4.7±0.8 a	8.8±1.4 a
Maize	Luancheng North	2018	C0	26.9±5.8 a	6.3±1.0 b	
			C7/30	28.6±5.1 a	6.8±1.2 b	
			C7/60	28.6±4.9 a	7.2±1.2 ab	
			C10/30	32.5±6.5 a	8.1±1.1 a	
			C10/60	29.7±2.9 a	7.3±0.9 ab	
Maize	Luancheng South	2018	C0	26.7±3.8 b	6.6±1.2 b	11.9±1.6
			C7/30	29.4±5.3 ab	7.7±1.2 ab	14±2.0
			C7/60	31.7±1.4 a	8.5±0.3 a	16.8±1.4
			C10/30	28.8±4.2 ab	8.2±0.8 a	18.6±2.8
			C10/60	28.3±4.8 ab	7.5±1.2 ab	14.8±2.2

Units: Y_B, Mg/ha; Y_G, Mg/ha; W_{root}, g/plant.

6. General discussion

6.1 Introduction

Soil compaction has been called a 'soil threat' as it causes deterioration or loss of soil functions. Compacted subsoils are especially a concern, because compacted subsoils are not easily recognized and are difficult to remediate. Compacted subsoils may have been formed by natural processes and factors (e.g., glaciation, illuviation of soil colloids, sodification, trampling animals) and by anthropogenic activities (e.g., machinery with high axle loads, inappropriate soil cultivation, frequent flood irrigation). The increasing weight of agricultural machinery is considered to be a main cause of subsoil compaction currently (Schonning et al., 2015; Keller et al., 2019).

The functioning and remediation of compacted subsoils in agriculture have been studied for more than a century now. Most of these studies have been conducted in field experiments and laboratories, and have been supported by simulation modeling. Relatively few studies have been conducted in farmland and in smallholder agriculture. As a result, there is little knowledge of the nature and spatial variation of compacted subsoils in practice, and about soil compaction in smallholder agriculture, where there is no or less influence of heavy machinery. Studies examining remediation measures for compacted subsoils have shown that these measure can be effective, but that their impact is often of short duration and that there are negative side effects (e.g., Schneider et al., 2017). Hence, there is a continuous search for more effective soil compaction prevention, remediation and alleviation measures with less negative side-effects, and for improved tillage practices, including no-till and reduced till.

The general objective of my PhD thesis research was to increase the understanding of spatial variations in soil compaction in farmers' fields, and of the efficacy of measures aimed at the prevention, alleviation and remediation of soil compaction. The specific research objectives were:

i. to review the recent (from 2000) literature on measures aimed at the prevention, alleviation and remediation of soil compaction, and to examine possible difference between small-holder and mechanized agriculture;
ii. to examine the relationships between spatial variations in subsoil compaction and spatial variations in soil properties, crop yield and nitrous oxide emissions in farmers' fields;

iii. to examine the effects of four soil tillage practices on soil bulk density, soil carbon and nutrient sequestration and crop yield in a long-term field experiment;
iv. to develop and test a prototype measure in the field for high-precision amelioration of compacted subsoil in small-holder agriculture and mechanized agriculture.

In this chapter, the main findings of my PhD thesis research are highlighted and discussed in a broader context. The chapter ends with a conclusion section, and a section in which future research needs are suggested.

6.2 Main findings

Measures for managing soil compaction can be classified into 3 groups according to their strategies, i.e., prevention, amelioration, and alleviation. According to my literature review presented in Chapter 2, it is clear that the emphasis in research during the last 20 years has been on testing prevention measures in mechanized agriculture, and on testing remediation and alleviation measures in small-holder agriculture. The effectiveness of the three strategies, expressed in crop yield or soil bulk density changes, turned out to be rather similar in mechanized and small-holder agriculture. Controlled traffic had a positive effect on crop yield in both mechanized agriculture (+38%) and small-holder agriculture (+16%), and led to a lower soil bulk density in topsoil and subsoil (range: −4% to −6%). No-till had negative effects on crop yield and increased bulk density, in both mechanized and small-holder agriculture. Deep tillage and subsoiling had positive effects on crop yields (up to +10%)

Soil bulk density and soil penetration resistance were mostly used as state indicators for assessing soil compaction. However, bulk density is not a sensitive indicator (effect sizes of measures were small (<10%)), and soil penetration resistance is highly sensitive to variations in soil moisture content. Effect sizes of crop yield as an impact indicator were relatively large, but variable because of interfering factors (climate, soil texture). My literature review reveals that prevention measures have to be prioritized, but that amelioration and alleviation are often equally needed and also effective, depending on site-specific conditions. Hence, a toolbox of soil compaction prevention, amelioration, and alleviation measures is needed, with measures adjusted to site-specific conditions.

Within-field spatial variations in bulk density of the subsoil and soil penetration resistance were relatively small. Mean soil bulk density in the sub-soil (30–35 cm and 50-55 cm) ranged between fields from 1.36 ± 0.08 to 1.60 ± 0.11 g cm^{-3}. Mean wheat yields ranged between fields and years from 7.6 ± 0.6 and 11.3 ± 2.4 Mg ha^{-1}. Semi-variogram analyses showed that crop yields and soil properties were mostly spatially dependent; nugget-to-sill ratios were < 25% with ranges of 137 to 773 m, and ranges of crop yield were larger than ranges of soil properties. Within-field spatial variations in soil properties were not related to within-field spatial variations in wheat yield. However, the ratio of CO_2 to N_2O emissions had a negative relationship with soil bulk density, especially following N application; emissions of N_2O increased with an increase in soil bulk density. There was no specific threshold for subsoil bulk density beyond which emissions changed dramatically. Thus, potential N_2O emission is a sensitive indicator for increases in soil bulk density and thus for soil compaction.

In a long term field experiment with an irrigated winter wheat – summer maize double cropping system in North China Plain, it was found that no-tillage and reduced tillage treatments decreased winter wheat yields and tended to increase soil bulk density in the subsoil, relative to conventional moldboard plowing treatment. The average winter wheat yields were 18% lower under no-tillage and 6% lower under reduced tillage compared to the conventional moldboard plowing treatment, after 17 years (from 2001 to 2018). Tillage treatments did not significantly affect maize yields. Soil carbon stocks increased initially but decreased over time. In the surface layer (0–5 cm), SOC content of the no-till treatment increased by 34% between 2005 and 2012, and then remained more or less constant at a level of 1.45 g kg^{-1}. No-tillage and reduced tillage combined with straw return led to a clear accumulation of carbon, nitrogen and phosphorus in the surface layers of the soil. Soil bulk density ranged between 1.5 and 1.8 g cm^{-3} in the 20-30 cm layer, and was related to tillage treatments.

A prototype precision bore-hole method was developed and tested for ameliorating compacted subsoils planted with row crops in Odiliapeel, Netherland and Luancheng, China. Bore-holes varied in diameter (6 to 10 cm) and depth (30 to 60 cm) and were re-filled with loosened soil (without or with manure amendment); seeds were planted above the positions of the bore-holes. The bore-hole method was effective in enhancing the maize yield by ~30%, especially in Luancheng, where the subsoil was compacted at shallow depth (15-30 cm). Bore-hole diameter and bore-hole depth did not lead to statistically significant differences in crop yield. Roots grew preferentially in the bore-holes, but no statistically significant differences in root weight were found between treatments for depths of 0-20, 20-40 and 40-60 cm. Sorghum yield did not respond to the bore-hole treatments.

6.3 Effectiveness of soil compaction management measures

Meta-analysis of published results of research on measures addressing soil compaction has become a common method of synthesizing ‘the state of the art’. Thus, meta-analyses have been conducted in evaluations of compaction levels induced by traffic (Ampoorter et al., 2012), in examining the plant morphological and physiological attributes in compacted soils (Mariotti et al., 2020), and in examining the impacts of soil compaction on soil health indicators (Byrnes et al., 2018) and on GHG emissions (Hernandez-Ramirez et al., 2021). Meta-analysis studies on soil compaction remediation often focusing on one single measure or activity (i.e., deep tillage (Peralta et al., 2021; Schneider et al., 2017), earthworm activity (Van Groenigen et al., 2014), no tillage (Pittelkow et al., 2015b), or crop residue return (Li et al., 2019b).

Most studies focused on mechanized agriculture, with little or no attention for small-holder agriculture. Apart from natural processes and factors causing compacted (sub)soils, soil compaction in small-holder agriculture may be caused by practices of conservation agriculture, including no-tillage and reduced tillage, and by flood irrigation. Conservation agriculture has been recommended by the FAO (2008) as a concept for resource-efficient crop production, but its benefits are controversial (Giller et al., 2011). Subsoil compaction in conservation agriculture has been noticed in several studies (Abdalla et al., 2021; Brouder and Gomez-Macpherson, 2014). Results presented in Chapter 4 of my thesis indicate also that practices related to conservation agriculture may lead to subsoil compaction and to a decline in wheat yields.

It has been noted that the ongoing urbanization in small-holder farming countries has stimulated the mechanization of small-holder agriculture (Huo et al., 2020), and although the light-weight two-wheel tractors have low axle loads, traffic-induced soil compaction have been found in both topsoil and in subsoil in small-holder agriculture (Baudron et al., 2012). Results presented in Chapter 5 suggest that human induced compacted subsoils are at more shallow depth in small-holder agriculture than in mechanized agriculture. Thus, (sub)soil compaction in small-holder agriculture should not be neglected.

I did not find substantive differences between mechanized and small-holder agriculture in the effectiveness of different strategies for addressing subsoil compaction. This may suggest that the experiences from mechanized agriculture in general may be adopted also in small-holder agriculture, and vice versa. However, as indicated before, measures have to be adjusted to site-specific conditions, i.e., depend on soil properties, climate and cropping systems, irrespective of mechanized or small-holder agriculture.

I used mixed-effect models in the data analysis, which were superior compared to fixed-effect models and random-effect models. When a single parameter value is assumed common to all studies, fixed-effect models are usually selected; the variation in effect sizes then comes from the within-study variance (Table 6.1). However, random-effect models are used commonly when the parameters underlying studies have normal distributions (Higgins et al., 2009), and the models consider the possibility of correlation of within-study results (Yu et al., 2015). In my study, mixed-effect models were selected, where soil compaction managing measures were set as fixed effects and studies were set as random effects. In this case, the random study effect and random experiment effects nested within studies were all considered.

The drawback of mixed-effect models lies in that they estimate mean responses of dependent variables (yield, bulk density and penetration resistance) to independent variables (measures for soil compaction management), while the mean responses are only representative for average conditions of factors included in the regression model (Yu et al., 2016). The Akaike information criterion (AIC) may be used as a supplement to mixed-effect model analyses (Qin et al., 2015). In Chapter 2, the AIC was not included because I assumed that the results from each study were independent (between years and locations).

Table 6.1 *Differences between fixed effect model and random effect model in meta-analysis (summarized from Gurevitch, 2018)*

	Fixed-effect model	**Random-effect model**
Variation in effect sizes comes from	Within-study (sampling) variance	Sampling variance & between study variance (heterogeneity)
"true" effects	Same in all studies	Different between studies
Scope of application	Apply only to a given group of studies	Apply more generally

6.4 Spatial variations in soil compaction and soil functioning

Within-field spatial variations were examined in four fields of four different farms through random soil sampling, laboratory analyses and semi-variogram tools (Chapter 3). Spatial variation analysis is a common practice in mechanized agriculture, where farmers manage the field in a uniform way (Finger et al., 2019). Information about within-field spatial variations may help in selecting optimum field management practices and amendments to increase soil productivity (Lipiec and Usowicz, 2018).

Within-field variation in soil properties is often considered a crucial source of the heterogeneity in crop yields (Diacono et al., 2013), which was also taken as a hypothesis in my study. I focused on the relationship between soil bulk density and soil functioning, including crop productivity and soil C and N transformations and emissions. However, correlations coefficients (R^2) were less than 0.25 in the linear regression analysis between spatial variations in soil bulk density and soil texture on the one hand and spatial variations in crop yields on the other hand, in the 8 field * year combinations (except for field A in 2016), which suggests that the spatial variations in crop yield were not so much related to soil properties but to variations in field management and to random variations (Pittelkow et al., 2015a). However, the spatial variation in crop yield were relatively small.

Within-field variations in soil properties commonly increase with an increase in the size of the field (Ali et al., 2019). Most soil properties were spatially dependent; the range values were larger than 200 m for 8 out of the 11 soil variables examined in the field of 21 ha, which were indeed larger than the ranges in the smaller field of 5 ha (for 7 out of the 11 variables examined, the range was smaller than 40 m). The larger and more complex the within-field spatial variation is, the more difficult the field management will be. Spatial variations in soil texture may affect crop yields especially in sandy soils, due to their effects on soil water holding capacity (Galka et al., 2016; Jankowski et al., 2011). Spatial variations in subsoil compaction are not easily detected and when interactions with soil texture occur, may greatly complicate the relationships between soil texture and crop yield. The 4 fields examined in the Hoeksche Waard in my study had a light clay and sandy clay soil texture (more than 91% of the samples had a clay content between 11% and 27%), and the soil texture was spatially strongly dependent, but there were no clear interactions between soil texture and soil bulk density.

Large-scale spatial variation in soil productivity may be caused also by spatial variations and differences in cropping systems. Comparisons between mechanized and small-holder cropping systems have been discussed for long (Paudel et al., 2019; Van Loon et al., 2020). These studies often emphasize that small-holder systems may benefit from mechanization and that mechanized agriculture may benefit from practices of small-holder systems. Farmers in the Hoeksche Waard make use of GPS-controlled trafficking and yield maps, which is non-existing in small-holder systems (Lobo et al., 2017). Many farmers in small-holder systems cannot even afford a mini-tiller (Paudel et al., 2019). In recent years, unmanned aerial vehicles open up a new way of obtaining field information which is often more efficient than through field sampling and laboratory analyses. The use of these unmanned aerial vehicles possibly combined with simulation modeling and field tests, may also contribute to obtaining a better understanding of the spatial variations in soil bulk density in relation to soil functioning.

6.5 Prototyping a high-precision measure for compacted subsoil

A prototype of a high-precision bore-hole method for remediating compacted subsoil was designed, and tested in four field experiments in two countries. The potential advantages of this measure are i) high precision and effective, and ii) less risk of re-compaction. This measure was born out of the studies presented by (Laker and Nortjé, 2020; Raper and Bergtold, 2007). The bore-hole method increased crop yields in the two field experiments conducted in Luancheng and in one experimental treatment out of two experiments in Odiliapeel. The greater effectiveness of the bore-hole method in Luancheng is likely related to the shallow depth of the compacted soil layer (15-30 cm). In contrast, the compacted subsoil was >35 cm in Odiliapeel. From soil penetration charts, it was clear that the penetration resistance rapidly increased from a depth of ~20 cm, and that peak values were found at about 25 cm. Thus, the 30 cm deep borehole were able to remediate the most compacted soil layers in Luancheng, through which root could grow more easily. In the review of (Laker and Nortjé, 2020), the depth of the trenches were 45 cm and 90cm, while the compacted soil layers were deeper than 20 cm. They mentioned that the effectiveness of 45 cm trenches was greater than those of 90 cm deep.

The yield increases of the bore-hole treatment were relatively large (~30%), suggesting indeed that crop yields were reduced by the compacted subsoil in the control treatments, and that the bore-hole treatments were effective in remediating the compacted subsoils. However, the cause-effect relationship is not clear, although the beneficial effects of the bore-hole treatment is very likely related to increased root growth. Thereby, plants likely had access to more soil water and nutrients, which increased crop production. However, it cannot be excluded that other factors played a role too, including a better aeration of the (sub)soil, although only at a limited area. The yield effects of the bore-hole treatments tended to be larger than the overall mean yield effect of deep ploughing and subsoiling as presented in literature (e.g., Schroder et al., 2017). Evidently, the beneficial effects of the bore-hole treatments on crop yield are large enough to justify further studies and to explore the potentials of the bore-hole method fully.

The Luancheng experimental station provides good conditions for further testing the bore-hole method, as the station has rich experiences with various cropping systems, tillage practices and long-term field experimentation. Long term field experiments have been considered as “the only practical way of assessing the long-term sustainability and productivity of husbandry systems within the agro-ecological zone in which they exist” (Johnston and Poulton, 2018). Also, long-term experiments commonly offer convincing results of trends and dynamics instead of static snapshots (Bationo et al., 2012). The

Luancheng experimental station is part of Chinese ecosystem research network (CERN), the longest-lived ecological network in China (Fu et al., 2010). The Luancheng experimental station offers also the possibility to explore the potentials of bore-hole method under the conditions of climate change, given their rich experience with climate change research (Li et al., 2019a; Wang et al., 2018). Likely, the effects of the bore-hole method are enhanced under conditions of increased rainfall variability.

6.6 A toolbox of strategies in soil compaction management

The DPSIR framework provides a transparent approach for presenting and analyzing the cause–effect-response relationships in soil compaction (Fig 6.1). Establishing a DPSIR framework for a particular setting is an important but complex task, as more than one cause-effect relationship may have to be considered and described, noting that impacts in soil ecosystems can rarely be attributed to a single cause (Tscherning et al., 2012). In the soil compaction cause–effect chain, the driving force seems to come from the drive in agriculture to increase crop productivity and to lower production costs (e.g., Schjonning et al., 2015). However, a low awareness of the risk of soil compaction, variable weather condition and poor timing of field activities, and lack of appropriate machinery and agricultural advisory services may also play a role. The driving forces induce pressures (literarily) on the soil, which leads to soil densification and to a change in the state of the soil, which then may lead to negative impacts on soil functioning. The DPSIR framework is also instrumental for explaining the focus of the soil compaction prevention, amelioration and alleviation strategies (Fig. 6.1).

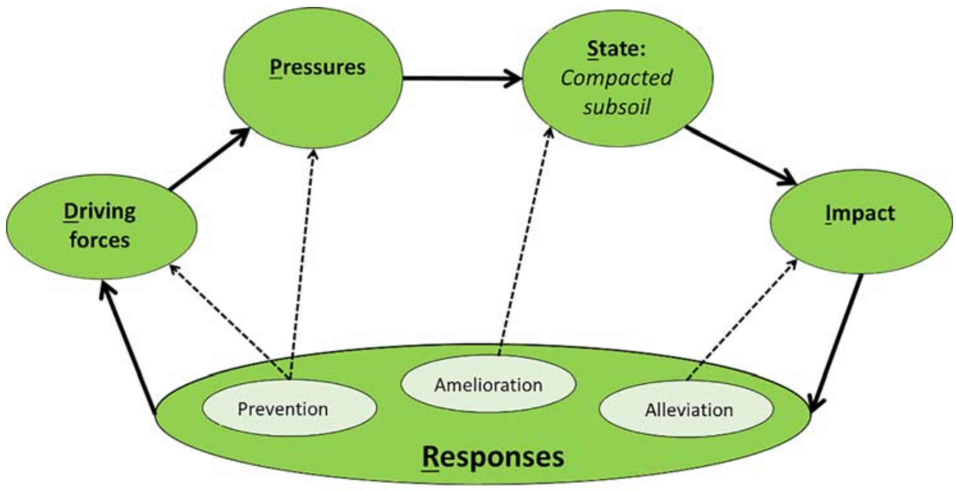
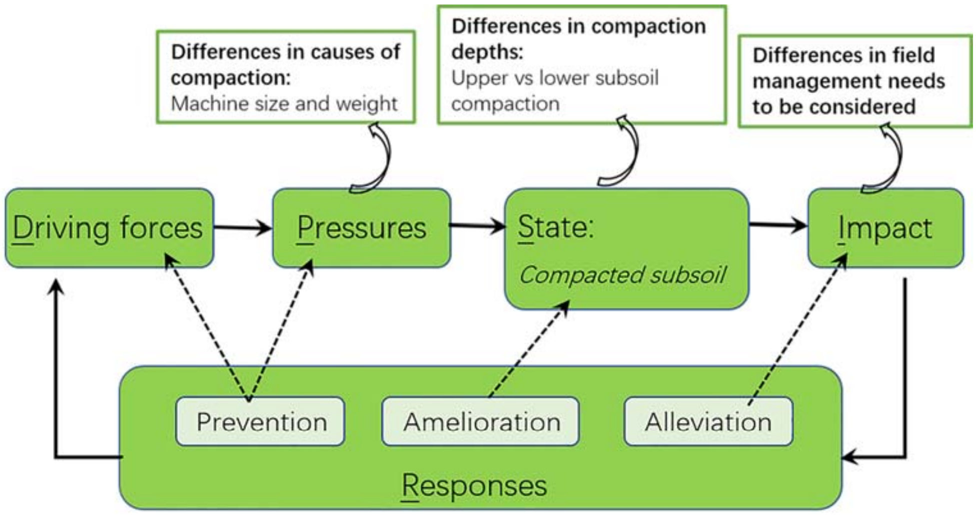


Fig. 6.1 *The DPSIR concept with focus on cause-effect soil compaction relationships (source: Chapter 2).*

Many farmers in the Netherlands are concerned about soil compaction and about the possible impacts of compacted subsoils on crop yields, but it does not mean that farmers can easily adjust practices and take preventive measures. Farmers in the Hoeksche Waard are forerunners and eager to learn new insights and tools. They invited us to examine spatial variations in soil bulk density, soil properties and soil nutrients. They were interested in the results of our investigations presented in Chapter 3, but wished to have clearer recommendations about the next steps and practical implications. Currently, many farmers in The Netherlands pay attention to spatial variations in crop yield and soil properties (Heijting et al., 2011); they practice precision agriculture, based on yield maps and based on visual observations, and they seek cooperation with scientists. Their high education level is very instrumental in this respect (De Weerd and Klandermans, 1999).

The impacts of compacted sub(soils) can be large. Compacted subsoils may decrease grain yield of cereals and soybean by 6 to 34% (Obour and Ugarte, 2021). Moreover, compacted soil increase the fuel use for soil tillage and often increase fertilizer and water inputs, to offset yield losses from compacted subsoils (Chamen et al., 2015). Emissions of N_2O are nearly doubled in compacted soils (Hernandez-Ramirez et al., 2021). Clearly, these impacts demand for prevention, amelioration, and alleviation measures (Fig 6.1). The idea of prevention and precaution is to exempt the driving forces of human induced soil compaction, thereby decreasing the pressures on the soil (Fig 6.1). Amelioration measures aim at remediating compacted (sub)soils, i.e., these measures aim at improving the state of the soil (e.g., soil bulk density, porosity). Alleviation measures aim to lower the negative impacts of compacted subsoils (e.g., nutrient and moisture deficiencies, water logging), through nutrient and moisture supplementation and/or extra drainage. During the last two decades, soil compaction prevention measures have been studied especially in mechanized agriculture, and amelioration and alleviation measures in small-holder agriculture. It is as yet unclear whether this difference in focus just reflects a time difference or a difference in effectiveness and practice. Evidently, this needs further study.

The suggested toolbox of various measures and strategies, as function of site-specific conditions, requires comprehension of the DPSIR framework in practice and greater monitoring efforts of the current state and impacts of soil compaction (Fig 6.2). Soil analytical laboratories should offer routine soil tests to farmers; these soil test should be able to provide a quick and robust assessment of (the spatial variations in) the 'densification state' of (sub)soils.



		Mechanized agriculture		Small holder farming	
Group	Measure	Application scope	Effect size	Application scope	Effect size
Prevention	Controlled traffic	Massive used	Sig. (+)	Less used	Sig. (+)
	No tillage	Less used	Sig. (-)	More used	Not Sig.
	Reduced tillage	More used	Not Sig.	Less used	Not Sig.
Amelioration	Subsoiling	Rarely used	Sig. (+)	Overwhelmingly	Sig. (+)
	Deep ploughing	Nearly the same	Sig. (+)	Nearly the same	Sig. (+)
Alleviation	Residue returning	Less used	Sig. (+)	More used	Sig. (+)
	Irrigation & manure input	Very rarely	-	Massive used	Sig. (+)
	Crop rotation	More used	Not Sig.	Less used	Sig. (+)

Fig. 6.2 *A toolbox of soil management strategies for mechanized and small-holder agricultural systems*

6.7 Conclusions

This PhD thesis provides an analysis of the possible impacts of spatial variations in soil bulk density in farmers' fields, and of the efficacy of measures aimed at the prevention, alleviation and remediation of soil compaction.

During the last 20 years, the research focus has been on how to prevent soil compaction in countries with mechanized agriculture, while the focus has been on amelioration and alleviation measures in countries with small-holder agriculture. Results presented in the literature during the last two decades indicated that there are no fundamental differences between mechanized and small-holder agricultural systems in the mean effect sizes of the measures. Controlled traffic had a positive effect on crop yield in countries with mechanized agriculture (+38%) and in small-holder agriculture (+16%), and led to a lower soil bulk density in topsoil and subsoil (−4% to −6%). No-till had negative effects on crop yield and increased soil bulk density. Deep tillage, including subsoiling, had positive effects on crop yields (+9% to +10%), while soil bulk density was decreased by about 3%. Prevention measures have to be prioritized, but amelioration and alleviation are often equally needed and also equally effective, depending on site-specific conditions.

The random sampling approach and semi-variograms were effective in characterizing field spatial variations in farmers' fields in the Hoeksche Waard, the Netherlands. Semi-variogram analyses showed that crop yields and soil properties were spatially dependent. There were no clear relationship between within-field variations in soil bulk density and within-field variations in wheat yields. The ratio of CO_2 to N_2O emissions had a negative relationship with soil bulk density, especially following N fertilization. There was no specific threshold for subsoil bulk density beyond which emissions changed dramatically. Potential N_2O emission is a more sensitive indicator for the effect of soil bulk density on soil functioning than wheat yield.

The long-term field experiment in Luancheng (China) revealed that no tillage and reduced tillage decreased winter wheat yields and were less effective in soil carbon sequestration compared to conventional moldboard ploughing with crop residue return. The average winter wheat yields were 18% lower under no-till and 6% lower under reduced tillage than under conventional moldboard plowing after 17 years (from 2001 to 2018). The lower yields in the no-till and reduced tillage treatments are likely related to the changes in soil bulk density with depth, but further studies are needed to unravel the cause-effect relationships more in-depth. Tillage treatments did not significantly affect maize yields in the winter wheat – summer maize double cropping system.

A prototype precision bore-hole method was developed and tested to enhance root and crop growth in compacted soils. The method was effective in enhancing maize yield by up to 30%. The method appeared to be more effective in fields with compacted subsoils at shallow depth (i.e., 15-30 cm) than in fields with the compacted subsoils at depth of >30 cm. Roots grew preferentially in the bore-holes, but no statistically significant differences in root weight were found between treatments for depths of 0-20, 20-40 and 40-60 cm. Sorghum did not respond to the bore-hole treatments. Further tests and developments are needed.

A toolbox of soil compaction prevention, amelioration and alleviation measures was proposed, to emphasize that different approaches are needed for the different conditions in practice.

6.8 Recommendations for further research

The actual densification state of (sub)soils in practice is not well known, because there is no routine monitoring of for example soil bulk density and porosity on farmers' fields. Such monitoring is needed to be able to diagnose which strategies are most effective to address soil compaction. As soil sampling and analyses for assessing the densification state of the subsoil are relatively expensive, there is a need for new indirect technologies, that make use of unmanned aerial vehicles and sensors.

Cooperation between farmers, scientists, and technique companies can be considered a win-win approach. Farmers may identify potential problems of their fields rather easily, but often do not understand the cause-effect relationships. Scientists take the research task, while technique companies develop the required sensors and technology. This type of cooperation is more common in The Netherlands than in China; evidently there is a need for greater cooperation of scientists with farmers and companies in China, building also on the experiences of the Science and Technology Backyards (e.g., Zhang et al., 2020)

Long-term fields experiment with tillage treatments remain necessary, also because impacts of tillage become apparent partly in the long term, as shown by the results of the experiment in Luancheng (Chapter 4). This holds as well for the prototype bore-hole method. More tests of the bore-hole method are needed, testing more different conditions, e.g., depth and diameter of bore-holes, irrigation treatments, crop residue mixed with bore-hole soils. It would be interesting also to test continuous grooves (narrow trenches) of 20 to 30 cm deep in Luancheng, instead of boreholes. Evidently, the concept of the prototype bore-hole method needs to be developed further.

With the further mechanization of crop production, the enlargement of farms and the development of contractors who do all the field work in China, there is also need for pre-cautionary measures, including raising awareness of the risk of soil compaction in China and other rapidly developing countries. Close attentions should be paid on the changes of soil bulk density and crop yields. Prevention measures are not easily taken by farmers because there is commonly no quick-response. Instead, the effect of deep ploughing or subsoiling, application of fertilizer and irrigation, create direct and 'visible' effects. This emphasizes the need of awareness raising.

References

Abdalla, K., Mutema, M., Chivenge, P., Chaplot, V., 2021. Controlled grazing of maize residues increased carbon sequestration in no-tillage system: a case of a smallholder farm in South Africa. Agronomy 11, 1421.

Aguilera, E., Lassaletta, L., Gattinger, A., Gimeno, B.S., 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agriculture, ecosystems & environment 168, 25-36.

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., van der Linden, J.P., Pires, S., Sommer, C., Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: a review Part 1. Machine/soil interactions. Soil & Tillage Research 73, 145-160.

Alam, M.K., Salahin, N., Islam, S., Begum, R., Hasanuzzaman, M., Islam, M., Rahman, M., 2017. Patterns of change in soil organic matter, physical properties and crop productivity under tillage practices and cropping systems in Bangladesh. The Journal of Agricultural Science 155, 216-238.

Alaoui, A., Lipiec, J., Gerke, H.H., 2011. A review of the changes in the soil pore system due to soil deformation: A hydrodynamic perspective. Soil & Tillage Research 115, 1-15.

Alaoui, A., Rogger, M., Peth, S., Bloeschl, G., 2018. Does soil compaction increase floods? A review. J Hydrol 557, 631-642.

Ali, A., Martelli, R., Lupia, F., Barbanti, L., 2019. Assessing multiple years' spatial variability of crop yields using satellite vegetation indices. Remote sensing 11, 2384.

Ali, O.N., Whittenton, J.B., Williams, J.J., Watts, F., Henry, W.B., 2018. Sub-optimal temperature effects on hybrid corn seed and seedling performance. Seed Technology, 129-142.

Altuntas, E., Ozgoz, E., Taser, O.F., 2005. Silage maize emergence is reduced by wheel traffic due to increased soil bulk density and penetration resistance. Acta Agriculturae Scandinavica, Section B-Soil & Plant Science 55, 30-35.

Alvarez, R., Steinbach, H.S., 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. Soil and tillage research 104, 1-15.

Amato, G., Ruisi, P., Frenda, A.S., Di Miceli, G., Saia, S., Plaia, A., Giambalvo, D., 2013. Long‐term tillage and crop sequence effects on wheat grain yield and quality. Agronomy Journal 105, 1317-1327.

Ampoorter, E., De Schrijver, A., Van Nevel, L., Hermy, M., Verheyen, K., 2012. Impact of mechanized harvesting on compaction of sandy and clayey forest soils: results of a meta-analysis. Annals of Forest Science 69, 533-542.

Antille, D.L., Peets, S., Galambosova, J., Botta, G.F., Rataj, V., Macak, M., Tullberg, J.N., Chamen, W.C.T., White, D.R., Misiewicz, P.A., Hargreaves, P.R., Bienvenido, J.F., Godwin, R.J., 2019. Review: Soil compaction and controlled traffic farming in arable and grass cropping systems. Agronomy Research 17, 653-682.

Aridhee, J., Abood, A.M., Kassar, F.H., Łysiak, G., Dakhil, M.M., 2020. Influence of tractor slip on some physical properties of the soil and fuel consumption at varying tillage depths and speed. Plant Archives 20, 141-145.

Arndt, W., 1966. The effect of traffic compaction on a number of soil properties. Journal of Agricultural Engineering Research 11, 182-187.

ASABE, 2006. Procedures for using and reporting data obtained with the soil cone penetrometer, EP542 FEB99, St. Joseph, Michigan, 1052-1055. American Society of Agricultural and Biological Engineers.

Asare, S., Rudra, R., Dickinson, W., Wall, G., 1999. Effect of freeze–thaw cycle on the parameters of the Green and Ampt infiltration equation. Journal of agricultural engineering research 73, 265-274.

Avidano, L., Gamalero, E., Cossa, G.P., Carraro, E., 2005. Characterization of soil health in an Italian polluted site by using microorganisms as bioindicators. Applied Soil Ecology 30, 21-33.

Awadhwal, N., Thierstein, G., 1985. Soil crust and its impact on crop establishment: a review. Soil and Tillage Research 5, 289-302.

Awal, R., Safeeq, M., Abbas, F., Fares, S., Deb, S.K., Ahmad, A., Fares, A., 2019. Soil physical properties spatial variability under long-term no-tillage corn. Agronomy 9, 750.

Ball, B., Bingham, I., Rees, R., Watson, C., Litterick, A., 2005. The role of crop rotations in determining soil structure and crop growth conditions. Canadian Journal of Soil Science 85, 557-577.

Banerjee, S., Walder, F., Büchi, L., Meyer, M., Held, A.Y., Gattinger, A., Keller, T., Charles, R., Van Der Heijden, M.G., 2019. Agricultural intensification reduces microbial network complexity and the abundance of keystone taxa in roots. The ISME journal 13, 1722-1736.

Bange, H.W., 2000. Global change - It's not a gas. Nature 408, 301-302.

Barik, K., Aksakal, E.L., Islam, K.R., Sari, S., Angin, I., 2014. Spatial variability in soil compaction properties associated with field traffic operations. Catena 120, 122-133.

Barnes, K.K., 1971. Compaction of agricultural soils.

Barrios, E., 2007. Soil biota, ecosystem services and land productivity. Ecological economics 64, 269-285.

Basso, B., Shuai, G.Y., Zhang, J.S., Robertson, G.P., 2019. Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. Sci Rep-Uk 9.

Batey, T., 2009. Soil compaction and soil management - a review. Soil Use and Management 25, 335-345.

Bationo, A., Waswa, B., Abdou, A., Bado, B., Bonzi, M., Iwuafor, E., Kibunja, C., Kihara, J., Mucheru, M., Mugendi, D., 2012. Overview of long term experiments in Africa. Lessons learned from long-term soil fertility management experiments in Africa, 1-26.

Baudron, F., Tittonell, P., Corbeels, M., Letourmy, P., Giller, K.E., 2012. Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe. Field crops research 132, 117-128.

Bengough, A.G., McKenzie, B., Hallett, P., Valentine, T., 2011. Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. Journal of experimental botany 62, 59-68.

Bennie, A., Botha, F., 1986. Effect of deep tillage and controlled traffic on root growth, water-use efficiency and yield of irrigated maize and wheat. Soil and Tillage research 7, 85-95.

Berisso, F.E., Schjonning, P., Keller, T., Lamande, M., Etana, A., de Jonge, L.W., Iversen, B.V., Arvidsson, J., Forkman, J., 2012. Persistent effects of subsoil compaction on pore size distribution and gas transport in a loamy soil. Soil & Tillage Research 122, 42-51.

Bessou, C., Mary, B., Leonard, J., Roussel, M., Grehan, E., Gabrielle, B., 2010. Modelling soil compaction impacts on nitrous oxide emissions in arable fields. European Journal of Soil Science 61, 348-363.

Blanco-Canqui, H., Lal, R., 2008. No-tillage and soil-profile carbon sequestration: An on-farm assessment.

Blum, W.E., 2005. Functions of soil for society and the environment. Reviews in Environmental Science and Bio/Technology 4, 75-79.

Bogunovic, I., Trevisani, S., Seput, M., Juzbasic, D., Durdevic, B., 2017. Short-range and regional spatial variability of soil chemical properties in an agro-ecosystem in eastern Croatia. Catena 154, 50-62.

Bölenius, E., Wetterlind, J., Keller, T., 2018. Can within field yield variation be explained using horizontal penetrometer resistance and electrical conductivity measurements? Results from three Swedish fields. Acta Agriculturae Scandinavica, Section B—Soil & Plant Science 68, 690-700.

Bouma, J., 2010. Implications of the knowledge paradox for soil science. Advances in agronomy 106, 143-171.
Bouma, J., 2014. Soil science contributions towards Sustainable Development Goals and their implementation: linking soil functions with ecosystem services. Journal of Plant Nutrition and Soil Science 177, 111-120.
Brais, S., Camire, C., 1998. Soil compaction induced by careful logging in the claybelt region of northwestern Quebec (Canada). Canadian Journal of Soil Science 78, 197-206.
Brouder, S.M., Gomez-Macpherson, H., 2014. The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence. Agriculture, ecosystems & environment 187, 11-32.
Brus, D.J., Van Den Akker, J.J., 2018a. How serious a problem is subsoil compaction in the Netherlands? A survey based on probability sampling. Soil 4, 37-45.
Brus, D.J., van den Akker, J.J.H., 2018b. How serious a problem is subsoil compaction in the Netherlands? A survey based on probability sampling. Soil 4, 37-45.
Büchi, L., Wendling, M., Amossé, C., Jeangros, B., Sinaj, S., Charles, R., 2017. Long and short term changes in crop yield and soil properties induced by the reduction of soil tillage in a long term experiment in Switzerland. Soil and Tillage Research 174, 120-129.
Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., 2018. Soil quality–A critical review. Soil Biology and Biochemistry 120, 105-125.
Busari, M.A., Kukal, S.S., Kaur, A., Bhatt, R., Dulazi, A.A., 2015. Conservation tillage impacts on soil, crop and the environment. International soil and water conservation research 3, 119-129.
Bussell, J., Crotty, F., Stoate, C., 2021. Comparison of Compaction Alleviation Methods on Soil Health and Greenhouse Gas Emissions. Land 10, 1397.
Byrnes, R.C., Eastburn, D.J., Tate, K.W., Roche, L.M., 2018. A global meta‐analysis of grazing impacts on soil health indicators. Journal of environmental quality 47, 758-765.
Cade‐Menun, B.J., Carter, M.R., James, D.C., Liu, C.W., 2010. Phosphorus forms and chemistry in the soil profile under long‐term conservation tillage: A phosphorus‐31 nuclear magnetic resonance study. Journal of Environmental Quality 39, 1647-1656.
Cambardella, C.A., Moorman, T.B., Novak, J., Parkin, T., Karlen, D., Turco, R., Konopka, A., 1994. Field‐scale variability of soil properties in central Iowa soils. Soil science society of America journal 58, 1501-1511.
Caon, L., Vargas, R., 2017. Threats to Soils: Global trends and Perspectives. Global Soil

Partnership Food and Agriculture Organization of the United Nations, Brajendra (Eds.) A contribution from the intergovernmental technical panel on soils. Global land outlook working paper.
Chamen, W.C.T., Moxey, A.P., Towers, W., Balana, B., Hallett, P.D., 2015. Mitigating arable soil compaction: A review and analysis of available cost and benefit data. Soil & Tillage Research 146, 10-25.
Chen, K., Shaw, B., 2022. Public communication of soil conservation practices: A large-scale content analysis of Wisconsin's agricultural trade publications. Journal of Soil and Water Conservation.
Chen, S., Yang, P., Zhang, Y., Dong, W., Hu, C., Oenema, O., 2022. Responses of cereal yields and soil carbon sequestration to four long-term tillage practices in the North China plain. Agronomy 12, 176.
Cheng-zhai, Z., Wei-sheng, Z., 1979. THE EFFECT OF SOIL COMPACTION ANE CLOD DISTRIBUTION ON THE GROWTH OF RICE. Acta Pedologica Sinica.
Cheng, W., OuYang, Z., Wu, L., 2005. Agro-ecosystems in Huang Huai Hai Plain. The ecosystems in China. Science Press, BeiJing (in Chinese).
Chimsah, F.A., Cai, L., Wu, J., Zhang, R., 2020. Outcomes of long-term conservation tillage research in Northern China. Sustainability 12, 1062.
Cleasby, T., 1964. Agricultural research in the sugar industry. South African Journal of Science 60, 42-48.
Commission, E., 2021. COM (2021) 699 Final: EU Soil Strategy for 2030 Reaping the Benefits of Healthy Soils for People, Food, Nature and Climate. European Commission Brussels, Belgium.
Coppens, F., Garnier, P., De Gryze, S., Merckx, R., Recous, S., 2006. Soil moisture, carbon and nitrogen dynamics following incorporation and surface application of labelled crop residues in soil columns. European journal of soil science 57, 894-905.
Corbeels, M., Marchão, R.L., Neto, M.S., Ferreira, E.G., Madari, B.E., Scopel, E., Brito, O.R., 2016. Evidence of limited carbon sequestration in soils under no-tillage systems in the Cerrado of Brazil. Sci Rep-Uk 6, 1-8.
Council, N.R., 2009. Frontiers in soil science research: Report of a workshop. National Academies Press.
Crittenden, S.J., Huerta, E., de Goede, R.G.M., Pulleman, M.M., 2015. Earthworm assemblages as affected by field margin strips and tillage intensity: An on-farm approach. European Journal of Soil Biology 66, 49-56.

Czyz, E.A., 2004. Effects of traffic on soil aeration, bulk density and growth of spring barley. Soil & Tillage Research 79, 153-166.
Daniells, I.G., 2012. Hardsetting soils: a review. Soil Research 50, 349-359.
de Moraes, M.T., Debiasi, H., Franchini, J.C., Mastroberti, A.A., Levien, R., Leitner, D., Schnepf, A., 2020. Soil compaction impacts soybean root growth in an Oxisol from subtropical Brazil. Soil and Tillage Research 200, 104611.
De Weerd, M., Klandermans, B., 1999. Group identification and political protest: farmers' protest in the Netherlands. European Journal of Social Psychology 29, 1073-1095.
Diacono, M., Rubino, P., Montemurro, F., 2013. Precision nitrogen management of wheat. A review. Agronomy for Sustainable Development 33, 219-241.
Domzal, H., 1977. influence of the solid phase density on the air and water capacities of brown loess soils. Zesz Probl Postepow Nauk Roln.
Dong, W., Hu, C., Chen, S., Zhang, Y., 2009. Tillage and residue management effects on soil carbon and CO2 emission in a wheat–corn double-cropping system. Nutrient Cycling in Agroecosystems 83, 27-37.
Dong, W., Hu, C., Zhang, Y., Wu, D., 2012. Gross mineralization, nitrification and N 2 O emission under different tillage in the North China Plain. Nutrient Cycling in Agroecosystems 94, 237-247.
Drew, M., Saker, L., 1980. Assessment of a rapid method, using soil cores, for estimating the amount and distribution of crop roots in the field. Plant and Soil 55, 297-305.
Drosos, M., Vinci, G., Spaccini, R., Piccolo, A., 2020. Molecular dynamics of organic matter in a tilled soil under short term wheat cultivation. Soil and Tillage Research 196, 104448.
Du, Z., Ren, T., Hu, C., 2010. Tillage and residue removal effects on soil carbon and nitrogen storage in the North China Plain. Soil Science Society of America Journal 74, 196-202.
EC, C., 2006. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Thematic Strategy for Soil Protection. Commission of the European Communities, Brussels 231.
Eckert, D., 1984. Tillage System× Planting Date Interactions in Corn Production 1. Agronomy Journal 76, 580-582.
Ecorys, 2007. Green- blue veining: agrobiodiversity as innovation for sustainable agriculture, ECORYS Nederland BV, Rotterdam. 27 pp.
Eriksson, J., 1975. Influence of extremely heavy traffic on clay soil. Grundförbättring.
Fabiola, N., Giarola, B., da Silva, A.P., Imhoff, S., Dexter, A.R., 2003. Contribution of natural soil compaction on hardsetting behavior. Geoderma 113, 95-108.

FAO, 2017a. The future of food and agriculture–Trends and challenges. Food and Agriculture Organisation Rome.
FAO, 2021. Crop Prospects and Food Situation #2, Quarterly Global Report, Rome, Italy.
FAO, F., 2017b. The future of food and agriculture–Trends and challenges. Annual Report 296, 1-180.
Fen, W., ZHAI, L.-c., Ping, X., ZHANG, Z.-b., Baillo, E.H., Tolosa, L.N., Kimotho, R.N., JIA, X.-l., GUO, H.-q., 2021. Effects of deep vertical rotary tillage on the grain yield and resource use efficiency of winter wheat in the Huang-Huai-Hai Plain of China. Journal of Integrative Agriculture 20, 593-605.
Field, C.R., Dayer, A.A., Elphick, C.S., 2017. Landowner behavior can determine the success of conservation strategies for ecosystem migration under sea-level rise. P Natl Acad Sci USA 114, 9134-9139.
Finger, R., Swinton, S.M., El Benni, N., Walter, A., 2019. Precision farming at the nexus of agricultural production and the environment. Annual Review of Resource Economics 11, 313-335.
Flowers, M., Lal, R., 1998. Axle load and tillage effects on soil physical properties and soybean grain yield on a mollic ochraqualf in northwest Ohio. Soil and Tillage Research 48, 21-35.
Food, Nations, A.O.o.t.U., 2008. Investing in sustainable agricultural intensification: The role of conservation agriculture. A framework for action. FAO Rome.
Fu, B., Li, S., Yu, X., Yang, P., Yu, G., Feng, R., Zhuang, X., 2010. Chinese ecosystem research network: progress and perspectives. Ecological Complexity 7, 225-233.
Galka, B., Kabala, C., Karczewska, A., Sowinski, J., Jakubiec, J., 2016. Variability of soil properties in an intensively cultivated experimental field. Soil Science Annual 67, 10.
Gathala, M.K., Timsina, J., Islam, M.S., Rahman, M.M., Hossain, M.I., Harun-Ar-Rashid, M., Ghosh, A.K., Krupnik, T.J., Tiwari, T.P., McDonald, A., 2015. Conservation agriculture based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice–maize systems: Evidence from Bangladesh. Field Crops Research 172, 85-98.
Giacomini, S., Recous, S., Mary, B., Aita, C., 2007. Simulating the effects of N availability, straw particle size and location in soil on C and N mineralization. Plant and Soil 301, 289-301.
Giller, K.E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., Tittonell, P., 2011. A research agenda to explore the role of conservation agriculture in African smallholder farming systems. Field crops research 124, 468-472.
Graven, L., Carter, P., 1991. Seed quality effect on corn performance under conventional and

no‐tillage systems. Journal of production agriculture 4, 366-372.
Greene, R., Kinnell, P., Wood, J.T., 1994. Role of plant cover and stock trampling on runoff and soil-erosion from semi-arid wooded rangelands. Soil Research 32, 953-973.
Greiner, L., Keller, A., Grêt-Regamey, A., Papritz, A., 2017. Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services. Land use policy 69, 224-237.
Hakansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil & Tillage Research 53, 71-85.
Håkansson, I., Reeder, R.C., 1994. Subsoil compaction by vehicles with high axle load—extent, persistence and crop response. Soil and tillage research 29, 277-304.
Håkansson, I., Voorhees, W.B., Elonen, P., Raghavan, G., Lowery, B., Van Wijk, A., Rasmussen, K., Riley, H., 1987. Effect of high axle-load traffic on subsoil compaction and crop yield in humid regions with annual freezing. Soil and Tillage Research 10, 259-268.
Hallett, P., Balana, B., Towers, W., Moxey, A., Chamen, T., 2012. Studies to Inform Policy Development With Regard to Soil Degradation: Subproject A: Cost Curve for Mitigation of Soil Compaction.
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems - A review of the nature, causes and possible solutions. Soil & Tillage Research 82, 121-145.
Han, D., Wiesmeier, M., Conant, R.T., Kühnel, A., Sun, Z., Kögel‐Knabner, I., Hou, R., Cong, P., Liang, R., Ouyang, Z., 2018. Large soil organic carbon increase due to improved agronomic management in the North China Plain from 1980s to 2010s. Global change biology 24, 987-1000.
Hargreaves, P., Baker, K., Graceson, A., Bonnett, S., Ball, B., Cloy, J., 2019. Soil compaction effects on grassland silage yields and soil structure under different levels of compaction over three years. European Journal of Agronomy 109, 125916.
He, J., Shi, Y., Zhao, J., Yu, Z., 2019. Strip rotary tillage with subsoiling increases winter wheat yield by alleviating leaf senescence and increasing grain filling. The Crop Journal.
Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta‐analysis of response ratios in experimental ecology. Ecology 80, 1150-1156.
Heijting, S., De Bruin, S., Bregt, A., 2011. The arable farmer as the assessor of within-field soil variation. Precis Agric 12, 488-507.
Hemmat, A., Adamchuk, V., 2008. Sensor systems for measuring soil compaction: Review and analysis. Computers and electronics in agriculture 63, 89-103.
Herbek, J., Murdock, L., Blevins, R., 1986. Tillage System and Date of Planting Effects on

Yield of Corn on Soils with Restricted Drainage 1. Agronomy Journal 78, 824-826.
Hernandez-Ramirez, G., Ruser, R., Kim, D.-G., 2021. How does soil compaction alter nitrous oxide fluxes? A meta-analysis. Soil and Tillage Research 211, 105036.
Higgins, J.P., Thompson, S.G., Spiegelhalter, D.J., 2009. A re‐evaluation of random‐effects meta‐analysis. Journal of the Royal Statistical Society: Series A (Statistics in Society) 172, 137-159.
Hohn, M., 1998. Geostatistics and petroleum geology. Springer Science & Business Media.
Hoogmoed, W., 1987. Some aspects of crust formation on soils in semi-arid regions [a review article], Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, Patancheru, AP (India), 1-3 Dec 1983. ICRISAT.
Hoogmoed, W., Berkhout, J., Stroosnijder, L., 1992. Soil tillage options for water management under erratic-rainfall conditions, Tillage in arid and semi-arid areas, an international seminar, Rabat, Morocco, 22-23 april 1992, pp. 228-247.
Horn, R., Domzal, H., Slowinskajurkiewicz, A., Vanouwerkerk, C., 1995a. Soil Compaction Processes and Their Effects on the Structure of Arable Soils and the Environment. Soil & Tillage Research 35, 23-36.
Horn, R., Domżżał, H., Słowińska-Jurkiewicz, A., Van Ouwerkerk, C., 1995b. Soil compaction processes and their effects on the structure of arable soils and the environment. Soil and Tillage Research 35, 23-36.
Horn, R., Taubner, H., 1989. Effect of aggregation on potassium flux in a structured soil. Zeitschrift für Pflanzenernährung und Bodenkunde 152, 99-104.
Houšková, B., Montanarella, L., 2008. The natural susceptibility of European soils to compaction. Threats to Soil Quality in Europe EUR 23438, 23-35.
Huber, S., Prokop, G., Arrouays, D., Banko, G., Bispo, A., Jones, R., Kibblewhite, M., Lexer, W., Möller, A., Rickson, R., 2008. Environmental assessment of soil for monitoring: volume I, indicators & criteria. Office for the Official Publications of the European Communities, Luxembourg.
Huo, L.F., Liang, L., Abbas, A., White, D., Ding, Q.S., Wang, X.C., He, R.Y., 2020. Soil disturbance under small harvester traffic in paddy‐based smallholder farms in China. Agronomy Journal 112, 1441-1451.
Jaggard, K.W., Qi, A., Ober, E.S., 2010. Possible changes to arable crop yields by 2050. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2835-2851.
James, G., Witten, D., Hastie, T., Tibshirani, R., 2013. An introduction to statistical learning.

Springer.
Jankowski, M., Przewoźna, B., Bednarek, R., 2011. Topographical inversion of sandy soils due to local conditions in Northern Poland. Geomorphology 135, 277-283.
Jin, X., Bai, Z., Oenema, O., Winiwarter, W., Velthof, G., Chen, X., Ma, L., 2020. Spatial planning needed to drastically reduce nitrogen and phosphorus surpluses in China's agriculture. Environmental science & technology 54, 11894-11904.
Johnston, A., Poulton, P., 2018. The importance of long‐term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. European Journal of Soil Science 69, 113-125.
Jones, R., Verheijen, F., Reuter, H., Jones, A., 2008. Environmental assessment of soil for monitoring volume V: Procedures & protocols. Luxembourg: EUR23490 EN/5, Office for the Official Publications of the European Communities.
Jones, R.J., Spoor, G., Thomasson, A., 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil and Tillage Research 73, 131-143.
Kan, Z.-R., Liu, Q.-Y., He, C., Jing, Z.-H., Virk, A.L., Qi, J.-Y., Zhao, X., Zhang, H.-L., 2020. Responses of grain yield and water use efficiency of winter wheat to tillage in the North China Plain. Field Crops Research 249, 107760.
Känkänen, H., Alakukku, L., Salo, Y., Pitkänen, T., 2011. Growth and yield of spring cereals during transition to zero tillage on clay soils. European Journal of Agronomy 34, 35-45.
Karlen, D.L., Mausbach, M., Doran, J.W., Cline, R., Harris, R., Schuman, G., 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Science Society of America Journal 61, 4-10.
Kassambara, A., 2019. Practical Statistics in R II-Comparing Groups: Numerical Variables. Datanovia.
Keller, T., Colombi, T., Ruiz, S., Manalili, M.P., Rek, J., Stadelmann, V., Wunderli, H., Breitenstein, D., Reiser, R., Oberholzer, H., Schymanski, S., Romero-Ruiz, A., Linde, N., Weisskopf, P., Walter, A., Or, D., 2017. Long-Term Soil Structure Observatory for Monitoring Post-Compaction Evolution of Soil Structure. Vadose Zone J 16.
Keller, T., Lamandé, M., Peth, S., Berli, M., Delenne, J.-Y., Baumgarten, W., Rabbel, W., Radjai, F., Rajchenbach, J., Selvadurai, A., 2013. An interdisciplinary approach towards improved understanding of soil deformation during compaction. Soil and Tillage Research 128, 61-80.
Keller, T., Sandin, M., Colombi, T., Horn, R., Or, D., 2019a. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. Soil & Tillage Research 194.

Keller, T., Sandin, M., Colombi, T., Horn, R., Or, D., 2019b. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. Soil and Tillage Research 194, 104293.

Kempenaar, C., Mollema, R., Been, T., Boheemen, K.v., Biewenga, G., Burg, S.v.d., Wassenaer, L.v., Meij, K.v.d., Graumans, C., Horst, A.t., Janssen, S., Lokhorst, K., Sijbrandij, F., Steinbusch, M., Vlugt, P.v.d., Wal, T.v.d., 2020. Bottlenecks in precision agriculture at farm level - data management and exchange (in Dutch). Report WPR-10.18174/532701. Wageningen Research, p. 120.

Kodikara, J., Islam, T., Sounthararajah, A., 2018. Review of soil compaction: History and recent developments. Transp Geotech 17, 24-34.

Kong, L., 2014. Maize residues, soil quality, and wheat growth in China. A review. Agronomy for sustainable development 34, 405-416.

Kool, D.M., Wrage, N., Zechmeister-Boltenstern, S., Pfeffer, M., Brus, D., Oenema, O., Van Groenigen, J.W., 2010. Nitrifier denitrification can be a source of N2O from soil: a revised approach to the dual-isotope labelling method. European Journal of Soil Science 61, 759-772.

Kristensen, P., 2004. The DPSIR framework. Paper presented at the 27–29 September 2004 workshop on a comprehensive/detailed assessment of the vulnerability of water resources to environmental change in Africa using river basin approach. UNEP Headquarters, Nairobi, Kenya http://water. eionet. europa. eu/internal_reports/DPSIR_water. doc. Accessed 19.

Kumara, T.K., Kandpal, A., Pal, S., 2020. A meta-analysis of economic and environmental benefits of conservation agriculture in South Asia. Journal of environmental management 269, 110773.

Laker, M., Nortjé, G., 2020. Review of existing knowledge on subsurface soil compaction in South Africa. Advances in Agronomy 162, 143-197.

Lampurlanés, J., Angás, P., Cantero-Martınez, C., 2001. Root growth, soil water content and yield of barley under different tillage systems on two soils in semiarid conditions. Field Crops Research 69, 27-40.

Lebert, M., Böken, H., Glante, F., 2007. Soil compaction—indicators for the assessment of harmful changes to the soil in the context of the German Federal Soil Protection Act. Journal of Environmental Management 82, 388-397.

Ledermüller, S., Fick, J., Jacobs, A., 2021. Perception of the Relevance of Soil Compaction and Application of Measures to Prevent It among German Farmers. Agronomy 11, 969.

Lemaire, G., Charrier, X., 1996. Nitrogen uptake capacities of maize and sorghum crops in different nitrogen and water supply conditions. Agronomie 16, 231-246.

Leskiw, L.A., Welsh, C.M., Zeleke, T.B., 2012. Effect of subsoiling and injection of pelletized organic matter on soil quality and productivity. Canadian Journal of Soil Science 92, 269-276.

Li, J., Dong, W., Oenema, O., Chen, T., Hu, C., Yuan, H., Zhao, L., 2019a. Irrigation reduces the negative effect of global warming on winter wheat yield and greenhouse gas intensity. Science of the Total Environment 646, 290-299.

Li, Q., Bian, C., Liu, X., Ma, C., Liu, Q., 2015. Winter wheat grain yield and water use efficiency in wide-precision planting pattern under deficit irrigation in North China Plain. Agricultural Water Management 153, 71-76.

Li, Y., Li, Z., Cui, S., Jagadamma, S., Zhang, Q., 2019b. Residue retention and minimum tillage improve physical environment of the soil in croplands: A global meta-analysis. Soil and Tillage Research 194, 104292.

Li, Y., Li, Z., Cui, S., Zhang, Q., 2020. Trade-off between soil pH, bulk density and other soil physical properties under global no-tillage agriculture. Geoderma 361, 114099.

Libohova, Z., Seybold, C., Wysocki, D., Wills, S., Schoeneberger, P., Williams, C., Lindbo, D., Stott, D., Owens, P.R., 2018. Reevaluating the effects of soil organic matter and other properties on available water-holding capacity using the National Cooperative Soil Survey Characterization Database. Journal of Soil and Water Conservation 73, 411-421.

Lipiec, J., Arvidsson, J., Murer, E., 2003. Review of modelling crop growth, movement of water and chemicals in relation to topsoil and subsoil compaction. Soil & Tillage Research 73, 15-29.

Lipiec, J., Usowicz, B., 2018. Spatial relationships among cereal yields and selected soil physical and chemical properties. Science of the Total Environment 633, 1579-1590.

Liu, S., Song, F., Zhu, X., Xu, H., 2012. Dynamics of root growth and distribution in maize from the black soil region of NE China. J. Agric. Sci 4, 21-30.

Liu, X., Feike, T., Shao, L., Sun, H., Chen, S., Zhang, X., 2016. Effects of different irrigation regimes on soil compaction in a winter wheat–summer maize cropping system in the North China Plain. Catena 137, 70-76.

Lloyd, C.D., 2005. Assessing the effect of integrating elevation data into the estimation of monthly precipitation in Great Britain. J Hydrol 308, 128-150.

Lobo, C., Chattopadhyay, N., Rao, K., 2017. Making smallholder farming climate-smart. Economic and Political Weekly, LII 52, 53-58.

Lowder, S.K., Skoet, J., Raney, T., 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Development 87, 16-29.

Lozano-García, B., Parras-Alcántara, L., 2014. Changes in soil properties and soil solution nutrients due to conservation versus conventional tillage in Vertisols. Archives of Agronomy and Soil Science 60, 1429-1444.

Lundy, M.E., Pittelkow, C.M., Linquist, B.A., Liang, X., van Groenigen, K.J., Lee, J., Six, J., Venterea, R.T., van Kessel, C., 2015. Nitrogen fertilization reduces yield declines following no-till adoption. Field Crops Research 183, 204-210.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, ecosystems & environment 139, 224-231.

Lutz, J., 1952. Mechanical impendence and plant growth. Soil physical conditions and plant growth. Agronomy monographs. Academic press, New York.

Machado, T.M., Lancas, K.P., 2016. PROTOTYPE FOR SOIL MECHANICAL RESISTANCE MEASUREMENT WITH CHISEL PLOW AUTOMATED CONTROL. Engenharia Agricola 36, 646-655.

Macholdt, J., Honermeier, B., 2017. Yield stability in winter wheat production: a survey on German farmers' and advisors' views. Agronomy 7, 45.

Madejón, E., Murillo, J., Moreno, F., López, M., Arrúe, J.L., Álvaro-Fuentes, J., Cantero, C., 2009. Effect of long-term conservation tillage on soil biochemical properties in Mediterranean Spanish areas. Soil and Tillage Research 105, 55-62.

Maestrini, B., Basso, B., 2018. Drivers of within-field spatial and temporal variability of crop yield across the US Midwest. Sci Rep-Uk 8.

Maillard, É., Angers, D.A., 2014. Animal manure application and soil organic carbon stocks: A meta‐analysis. Global Change Biology 20, 666-679.

Makange, N.R., Ji, C., Nyalala, I., Sunusi, I.I., Opiyo, S., 2021. Prediction of precise subsoiling based on analytical method, discrete element simulation and experimental data from soil bin. Sci Rep-Uk 11, 1-12.

Mariotti, B., Hoshika, Y., Cambi, M., Marra, E., Feng, Z., Paoletti, E., Marchi, E., 2020. Vehicle-induced compaction of forest soil affects plant morphological and physiological attributes: a meta-analysis. Forest Ecology and Management 462, 118004.

Marra, E., Cambi, M., Fernandez-Lacruz, R., Giannetti, F., Marchi, E., Nordfjell, T., 2018. Photogrammetric estimation of wheel rut dimensions and soil compaction after increasing numbers of forwarder passes. Scandinavian Journal of Forest Research 33, 613-620.

Martin-Rueda, I., Munoz-Guerra, L., Yunta, F., Esteban, E., Tenorio, J., Lucena, J., 2007. Tillage and crop rotation effects on barley yield and soil nutrients on a Calciortidic Haploxeralf. Soil and Tillage Research 92, 1-9.

Martínez, E., Fuentes, J.-P., Silva, P., Valle, S., Acevedo, E., 2008. Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile. Soil and Tillage Research 99, 232-244.

Mathers, A., Lotspeich, F., Laase, G., Wilson, G., 1966. Strength of compacted Amarillo fine sandy loam as influenced by moisture, clay content, and exchangeable cation. Soil Science Society of America Journal 30, 788-791.

Matowo, P.R., Pierzynski, G.M., Whitney, D., Lamond, R.E., 1999. Soil chemical properties as influenced by tillage and nitrogen source, placement, and rates after 10 years of continuous sorghum. Soil and Tillage Research 50, 11-19.

Matthieu, D.E., Bowman, D.C., Thapa, B.B., Cassel, D.K., Rufty, T.W., 2011. Turfgrass root response to subsurface soil compaction. Communications in soil science and plant analysis 42, 2813-2823.

McKevith, B., 2004. Nutritional aspects of cereals. Nutrition Bulletin 29, 111-142.

Medvedev, V., Cybulko, W., 1995. Soil criteria for assessing the maximum permissible ground pressure of agricultural vehicles on Chernozem soils. Soil and Tillage Research 36, 153-164.

Mitchell, F., Berry, W., 2001. The effects and management of compaction in agricultural soils, Proc S Afr Sug Technol Ass. Citeseer, pp. 118-124.

Moraes, M.T.d., Silva, V.R.d., Zwirtes, A.L., Carlesso, R., 2014. Use of penetrometers in agriculture: a review. Engenharia Agrícola 34, 179-193.

Mueller, L., Kay, B.D., Hu, C.S., Li, Y., Schindler, U., Behrendt, A., Shepherd, T.G., Ball, B.C., 2009. Visual assessment of soil structure: Evaluation of methodologies on sites in Canada, China and Germany Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals. Soil & Tillage Research 103, 178-187.

Mujdeci, M., Isildar, A.A., Uygur, V., Alaboz, P., Unlu, H., Senol, H., 2017. Cooperative effects of field traffic and organic matter treatments on some compaction-related soil properties. Solid Earth 8, 189-198.

Mulholland, B., Fullen, M., 1991. Cattle trampling and soil compaction on loamy sands. Soil use and management 7, 189-193.

Mullins, C., MacLeod, D., Northcote, K., Tisdall, J., Young, I., 1990. Hardsetting soils: behavior, occurrence, and management, Advances in soil science. Springer, pp. 37-108.

Nawaz, M.F., Bourrie, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agronomy for sustainable development 33, 291-309.

NEN5704, 1996. Soil – Sample preparation of soil. Extraction with calcium chloride solution (0.01 mol/L). Available at: http://www.nen.nl (accessed August 2010). (In Dutch).

Njøs, A., 1976. Long term effects of tractor traffic in two field experiments in Norway. Rapporter fraan Jordbearbetningsavdelningen-Lantbrukshoegskolan (Sweden).
Nouri, A., Lee, J., Yin, X., Tyler, D.D., Saxton, A.M., 2019. Thirty-four years of no-tillage and cover crops improve soil quality and increase cotton yield in Alfisols, Southeastern USA. Geoderma 337, 998-1008.
Obour, P.B., Ugarte, C.M., 2021. A meta-analysis of the impact of traffic-induced compaction on soil physical properties and grain yield. Soil and Tillage Research 211, 105019.
Ogle, S.M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F.J., McConkey, B., Regina, K., Vazquez-Amabile, G.G., 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Sci Rep-Uk 9, 1-8.
Ogle, S.M., Swan, A., Paustian, K., 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agriculture, Ecosystems & Environment 149, 37-49.
Oldeman, L.R., 1991. World map of the status of human-induced soil degradation, An explanatory note, Global assessment of soils degradation, GLASOD. The Map Sheets.
Pagliai, M., Raglione, M., Panini, T., Maletta, M., La Marca, M., 1995. The structure of two alluvial soils in Italy after 10 years of conventional and minimum tillage. Soil and Tillage Research 34, 209-223.
Panayiotopoulos, K., Papadopoulou, C., Hatjiioannidou, A., 1994. Compaction and penetration resistance of an Alfisol and Entisol and their influence on root growth of maize seedlings. Soil and Tillage Research 31, 323-337.
Panayiotopoulos, K., Salonikiou, E., Siaga, K., Germanopoulou, V., Skaperda, S., 2003. Effect of uniaxial compression on water retention, hydraulic conductivity and the penetration resistance of six Greek soils. International agrophysics 17.
Passioura, J., Leeper, G., 1963. Soil compaction and manganese deficiency. Nature 200, 29.
Patterson, D., Chamen, W., Richardson, C., 1980. Long-term experiments with tillage systems to improve the economy of cultivations for cereals. Journal of Agricultural Engineering Research 25, 1-35.
Paudel, G.P., Kc, D.B., Khanal, N.P., Justice, S.E., McDonald, A.J., 2019. Smallholder farmers' willingness to pay for scale-appropriate farm mechanization: Evidence from the mid-hills of Nepal. Technology in society 59, 101196.
Pedrotti, A., de Araújo Filho, R.N., Assunção, S.J.R., Gomes Filho, R.R., de Oliveira, F.C.C., Holanda, F.S.R., Piscoya, V.C., Cunha Filho, M., 2019. Soil Mechanical Resistance

Penetration after Fifteen Years with Previous Crops and Tillage Systems and Productivity of Green Corn Cob in Northeast Brazil. Journal of Experimental Agriculture International, 1-9.
Peng, Z., Wang, L., Xie, J., Li, L., Coulter, J.A., Zhang, R., Luo, Z., Cai, L., Carberry, P., Whitbread, A., 2020. Conservation tillage increases yield and precipitation use efficiency of wheat on the semi-arid Loess Plateau of China. Agricultural Water Management 231, 106024.
Pennock, D., McKenzie, N., Montanarella, L., 2015. Status of the world's soil resources. Technical Summary FAO, Rome, Italy.
Peralta, G., Alvarez, C.R., Taboada, M.A., 2021. Soil compaction alleviation by deep non-inversion tillage and crop yield responses in no tilled soils of the Pampas region of Argentina. A meta-analysis. Soil and Tillage Research 211, 105022.
Piazza, G., Pellegrino, E., Moscatelli, M.C., Ercoli, L., 2020. Long-term conservation tillage and nitrogen fertilization effects on soil aggregate distribution, nutrient stocks and enzymatic activities in bulk soil and occluded microaggregates. Soil and Tillage Research 196, 104482.
Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., 2017. R Core Team (2017) nlme: linear and nonlinear mixed effects models. R package version 3.1-131. Computer software] Retrieved from https://CRAN. R-project. org/package= nlme.
Pittelkow, C.M., Liang, X., Linquist, B.A., Van Groenigen, K.J., Lee, J., Lundy, M.E., Van Gestel, N., Six, J., Venterea, R.T., Van Kessel, C., 2015a. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365-368.
Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015b. When does no-till yield more? A global meta-analysis. Field Crops Research 183, 156-168.
Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nature Climate Change 4, 678-683.
Pulido Moncada, M., Gabriels, D., Lobo, D., Rey, J.C., Cornelis, W.M., 2014. Visual field assessment of soil structural quality in tropical soils. Soil & Tillage Research 139, 8-18.
Qin, S., Hu, C., Clough, T.J., Luo, J., Oenema, O., Zhou, S., 2017. Irrigation of DOC-rich liquid promotes potential denitrification rate and decreases N2O/(N2O+ N2) product ratio in a 0–2 m soil profile. Soil Biology and Biochemistry 106, 1-8.
Qin, W., Hu, C., Oenema, O., 2015. Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis. Sci Rep-Uk 5, 1-13.
Qu, C., Li, B., Wu, H., Giesy, J.P., 2012. Controlling air pollution from straw burning in China calls for efficient recycling. ACS Publications.

Ranaivoson, L., Naudin, K., Ripoche, A., Affholder, F., Rabeharisoa, L., Corbeels, M., 2017. Agro-ecological functions of crop residues under conservation agriculture. A review. Agronomy for sustainable development 37, 1-17.
Raper, R.L., Bergtold, J.S., 2007. In-row subsoiling: A review and suggestions for reducing cost of this conservation tillage operation. Applied Engineering in Agriculture 23, 463-471.
RCoreTeam, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.
Rietra, R., Heinen, M., Oenema, O., 2022. A Review of Crop Husbandry and Soil Management Practices Using Meta-Analysis Studies: Towards Soil-Improving Cropping Systems. Land 11, 255.
Robertson, G., 2008. GS+:"Geostatistics for the Environmental Sciences", Gamma Design Software, Plainwell, Michigan USA. Pdf document available for free at: https://geostatistics. com/files/GSPlusUserGuide. pdf.
Robertson, G.P., Groffman, P.M., 2015. Nitrogen transformations. Academic Press, Massachusetts, USA.
Ruser, R., Flessa, H., Russow, R., Schmidt, G., Buegger, F., Munch, J.C., 2006. Emission of N2O, N-2 and CO2 from soil fertilized with nitrate: Effect of compaction, soil moisture and rewetting. Soil Biology & Biochemistry 38, 263-274.
Rusinamhodzi, L., Corbeels, M., Van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agronomy for sustainable development 31, 657.
Schjønning, P., de Jonge, L.W., Munkholm, L.J., Moldrup, P., Christensen, B., Olesen, J., 2012. Clay dispersibility and soil friability—Testing the soil clay-to-carbon saturation concept. Vadose Zone J 11.
Schjønning, P., van den Akker, J.J., Keller, T., Greve, M.H., Lamandé, M., Simojoki, A., Stettler, M., Arvidsson, J., Breuning-Madsen, H., 2015. Driver-pressure-state-impact-response (DPSIR) analysis and risk assessment for soil compaction—a European perspective. Advances in agronomy 133, 183-237.
Schjonning, P., van den Akker, J.J.H., Keller, T., Greve, M.H., Lamande, M., Simojoki, A., Stettler, M., Arvidsson, J., Breuning-Madsen, H., 2015. Driver-Pressure-State-Impact-Response (DPSIR) Analysis and Risk Assessment for Soil Compaction-A European Perspective. Adv Agron 133, 183-237.
Schneider, F., Don, A., Hennings, I., Schmittmann, O., Seidel, S.J., 2017. The effect of deep tillage on crop yield–What do we really know? Soil and tillage research 174, 193-204.

Schulte, R.P., Creamer, R.E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C., O'huallachain, D., 2014. Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environmental Science & Policy 38, 45-58.

Schulte, R.P., O'Sullivan, L., Vrebos, D., Bampa, F., Jones, A., Staes, J., 2019. Demands on land: Mapping competing societal expectations for the functionality of agricultural soils in Europe. Environmental Science & Policy 100, 113-125.

Schuurman, J.J., Goedewaagen, M.A.J., 1971. Methods for examination of root systems and roots, 2nd ed ed. Pudoc, Wagenignen.

Shah, A.N., Tanveer, M., Shahzad, B., Yang, G., Fahad, S., Ali, S., Bukhari, M.A., Tung, S.A., Hafeez, A., Souliyanonh, B., 2017a. Soil compaction effects on soil health and cropproductivity: an overview. Environmental science and pollution research international 24, 10056-10067.

Shah, A.N., Tanveer, M., Shahzad, B., Yang, G.Z., Fahad, S., Ali, S., Bukhari, M.A., Tung, S.A., Hafeez, A., Souliyanonh, B., 2017b. Soil compaction effects on soil health and crop productivity: an overview. Environ Sci Pollut R 24, 10056-10067.

Shaheb, M.R., Venkatesh, R., Shearer, S.A., 2021. A Review on the Effect of Soil Compaction and its Management for Sustainable Crop Production. Journal of Biosystems Engineering, 1-23.

Shcherbak, I., Robertson, G.P., 2019. Nitrous Oxide (N2O) Emissions from Subsurface Soils of Agricultural Ecosystems. Ecosystems 22, 1650-1663.

Singh, V., van Oosterom, E.J., Jordan, D.R., Messina, C.D., Cooper, M., Hammer, G.L., 2010. Morphological and architectural development of root systems in sorghum and maize. Plant and Soil 333, 287-299.

Sitaula, B.K., Hansen, S., Sitaula, J.I.B., Bakken, L.R., 2000. Methane oxidation potentials and fluxes in agricultural soil: Effects of fertilisation and soil compaction. Biogeochemistry 48, 323-339.

Soane, B., Blackwell, P., Dickson, J., Painter, D., 1980. Compaction by agricultural vehicles: A review I. Soil and wheel characteristics. Soil and Tillage Research 1, 207-237.

Soane, B., Van Ouwerkerk, C., 1994. Soil compaction problems in world agriculture, Developments in Agricultural Engineering. Elsevier, pp. 1-21.

Soane, B., Van Ouwerkerk, C., 1995. Implications of soil compaction in crop production for the quality of the environment. Soil and Tillage Research 35, 5-22.

Soane, B.D., 1976. Gamma-ray transmission systems for the in situ measurement of soil packing state-review paper. Scottish Institute of Agricultural Engineering-Biennial Report.

Sonderegger, T., Pfister, S., 2021. Global Assessment of Agricultural Productivity Losses from Soil Compaction and Water Erosion. Environmental Science & Technology 55, 12162-12171.
Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., 2020. Methods of soil analysis, part 3: Chemical methods. John Wiley & Sons.
Spoor, G., 1994. Application of mole drainage in the solution of subsoil management problems. Advances in Soil Science: Subsoil Management Techniques. Lewis Publishers, Chelsea, Michigan, 67-107.
Spoor, G., 2006. Alleviation of soil compaction: requirements, equipment and techniques. Soil Use and Management 22, 113-122.
Spoor, G., Tijink, F., Weisskopf, P., 2003. Subsoil compaction: risk, avoidance, identification and alleviation. Soil and tillage research 73, 175-182.
Staff, S., 2014. Keys to Soil Taxonomy, 12th Edn Washington. DC: Natural Resources Conservation Service, United States Department of Agriculture.[Google Scholar].
Steingrover, E.G., Geertsema, W., van Wingerden, W.K.R.E., 2010. Designing agricultural landscapes for natural pest control: a transdisciplinary approach in the Hoeksche Waard (The Netherlands). Landscape Ecol 25, 825-838.
Stelluti, M., Maiorana, M., De Giorgio, D., 1998. Multivariate approach to evaluate the penetrometer resistance in different tillage systems. Soil and Tillage Research 46, 145-151.
Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., De Courcelles, V.d.R., Singh, K., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems & Environment 164, 80-99.
Stolte, J., Tesfai, M., Oygarden, L., Kvaerno, S., Keizer, J., Verheijen, F., Panagos, P., Ballabio, C., Hessel, R., 2016. Soil threats in Europe: status, methods, drivers and effects on ecosystem services: deliverable 2.1 RECARE project. European Commission DG Joint Research Centre.
Stolte, J., Tesfai, M., Øygarden, L., Kværnø, S., Keizer, J., Verheijen, F., Panagos, P., Ballabio, C., Hessel, R., 2015. Soil threats in Europe. Publications Office Luxembourg.
Su, Z., Zhang, J., Wu, W., Cai, D., Lv, J., Jiang, G., Huang, J., Gao, J., Hartmann, R., Gabriels, D., 2007. Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on the Loess Plateau, China. Agricultural Water Management 87, 307-314.
Taner, A., Arisoy, R.Z., Kaya, Y., Gültekin, I., Partigöç, F., 2015. The effects of various tillage systems on grain yield, quality parameters and energy indices in winter wheat production under the rainfed conditions. Fresenius Environ. Bull 24, 1463-1473.
Taylor, H.M., 1958. A Pneumatic Soil Compression Device1. Soil Science Society of America

Journal 22, 271.
Taylor, H.M., Brar, G.S., 1991. EFFECT OF SOIL COMPACTION ON ROOT DEVELOPMENT. Soil & Tillage Research 19, 111-119.
Taylor, J.C., Wood, G.A., Earl, R., Godwin, R.J., 2003. Soil factors and their influence on within-field crop variability, part II: Spatial analysis and determination of management zones. Biosystems Engineering 84, 441-453.
Techen, A.-K., Helming, K., Brüggemann, N., Veldkamp, E., Reinhold-Hurek, B., Lorenz, M., Bartke, S., Heinrich, U., Amelung, W., Augustin, K., 2020. Soil research challenges in response to emerging agricultural soil management practices. Advances in agronomy 161, 179-240.
Ten Berge, H., Schröder, J., Olesen, J., Cervera, J.-V.G., 2017. Research for AGRI Committee-Preserving agricultural soils in the EU.
Thorsøe, M.H., Noe, E.B., Lamandé, M., Frelih-Larsen, A., Kjeldsen, C., Zandersen, M., Schjønning, P., 2019. Sustainable soil management-Farmers' perspectives on subsoil compaction and the opportunities and barriers for intervention. Land Use Policy 86, 427-437.
Tian, S., Ning, T., Wang, Y., Liu, Z., Li, G., Li, Z., Lal, R., 2016. Crop yield and soil carbon responses to tillage method changes in North China. Soil and Tillage Research 163, 207-213.
Toliver, D.K., Larson, J.A., Roberts, R.K., English, B.C., De La Torre Ugarte, D.G., West, T.O., 2012. Effects of no ‐ till on yields as influenced by crop and environmental factors. Agronomy journal 104, 530-541.
Tóth, G., Li, X., 2013. Threats to the soil resource base of food security in China and Europe. Publications Office.
Troccoli, A., Maddaluno, C., Mucci, M., Russo, M., Rinaldi, M., 2015. Is it appropriate to support the farmers for adopting conservation agriculture? Economic and environmental impact assessment. Italian Journal of Agronomy 10, 169-177.
Tscherning, K., Helming, K., Krippner, B., Sieber, S., y Paloma, S.G., 2012. Does research applying the DPSIR framework support decision making? Land use policy 29, 102-110.
Tullberg, J., Antille, D.L., Bluett, C., Eberhard, J., Scheer, C., 2018. Controlled traffic farming effects on soil emissions of nitrous oxide and methane. Soil and Tillage Research 176, 18-25.
Tullberg, J., Yule, D., McGarry, D., 2007. Controlled traffic farming—from research to adoption in Australia. Soil and Tillage Research 97, 272-281.
Unger, P.W., Kaspar, T.C., 1994. SOIL COMPACTION AND ROOT-GROWTH - A REVIEW. Agronomy Journal 86, 759-766.
Usowicz, B., Lipiec, J., 2017. Spatial variability of soil properties and cereal yield in a cultivated

field on sandy soil. Soil and Tillage Research 174, 241-250.

Usowicz, B., Lipiec, J., 2021. Spatial variability of saturated hydraulic conductivity and its links with other soil properties at the regional scale. Sci Rep-Uk 11, 1-12.

Ussiri, D.A., Lal, R., 2009. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. Soil and Tillage Research 104, 39-47.

van den Akker, J., de Vries, F., Vermeulen, G., Hack-ten Broeke, M., Schouten, T., 2013. Risico op ondergrondverdichting in het landelijk gebied kaart. Alterra, Wageningen-UR.

van den Akker, J.J.H., 2008. Soil compaction. EUR 23490 EN/1., Environmental Assessment of Soil for Monitoring: Volume I Indicators & Criteria. . Office for the Official Publications of the European Communities, Luxembourg, pp. 107-124.

van den Akker, J.J.H., Hoogland, T., 2011. Comparison of risk assessment methods to determine the subsoil compaction risk of agricultural soils in The Netherlands. Soil & Tillage Research 114, 146-154.

van Erp, P.J., Houba, V.J.G., Van Beusichem, M.L., 1998. One hundredth molar calcium chloride extraction procedure. Part I: A review of soil chemical, analytical, and plant nutritional aspects. Communications in Soil Science and Plant Analysis 29, 1603-1623.

van Groenigen, J.W., Kuikman, P.J., de Groot, W.J.M., Velthof, G.L., 2005. Nitrous oxide emission from urine-treated soil as influenced by urine composition and soil physical conditions. Soil Biology & Biochemistry 37, 463-473.

Van Groenigen, J.W., Lubbers, I.M., Vos, H.M., Brown, G.G., De Deyn, G.B., Van Groenigen, K.J., 2014. Earthworms increase plant production: a meta-analysis. Sci Rep-Uk 4, 1-7.

Van Loon, J., Woltering, L., Krupnik, T.J., Baudron, F., Boa, M., Govaerts, B., 2020. Scaling agricultural mechanization services in smallholder farming systems: Case studies from sub-Saharan Africa, South Asia, and Latin America. Agricultural systems 180, 102792.

Van Ouwerkerk, C., 1968. Two model experiments on the durability of subsoil compaction. Netherlands Journal of Agricultural Science 16, 204-210.

Veihmeyer, F., Hendrickson, A.H., 1948. Soil density and root penetration. Soil science 65, 487-494.

Vereijken, P., 1997. A methodical way of prototyping integrated and ecological arable farming systems (I/EAFS) in interaction with pilot farms. European journal of agronomy 7, 235-250.

Vu, D., Tang, C., Armstrong, R., 2009. Tillage system affects phosphorus form and depth distribution in three contrasting Victorian soils. Soil Research 47, 33-45.

Wahlström, E.M., Kristensen, H.L., Thomsen, I.K., Labouriau, R., Pulido-Moncada, M.,

Nielsen, J.A., Munkholm, L.J., 2021. Subsoil compaction effect on spatio-temporal root growth, reuse of biopores and crop yield of spring barley. European Journal of Agronomy 123, 126225.
Wang, X., He, C., Liu, B., Zhao, X., Liu, Y., Wang, Q., Zhang, H., 2020. Effects of residue returning on soil organic carbon storage and sequestration rate in China’s croplands: A meta-analysis. Agronomy 10, 691.
Wang, Y., Li, X., Dong, W., Wu, D., Hu, C., Zhang, Y., Luo, Y., 2018. Depth-dependent greenhouse gas production and consumption in an upland cropping system in northern China. Geoderma 319, 100-112.
Weil, R., Benedetto, P., Sikora, L., Bandel, V., 1988. Influence of tillage practices on phosphorus distribution and forms in three Ultisols. Agronomy Journal 80, 503-509.
Weisskopf, P., Zihlmann, U., Wiermann, C., Horn, R., Anken, T., Diserens, E., 2000. Influences of conventional and onland ploughing on soil structure. Advances in GeoEcology, 73-81.
West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal 66, 1930-1946.
Wilkins, S.M., Wilkins, H., Wain, R., 1976. Chemical treatment of soil alleviates effects of soil compaction on pea seedling growth. Nature 259, 392-394.
Wrage-Monnig, N., Horn, M.A., Well, R., Muller, C., Velthof, G., Oenema, O., 2018. The role of nitrifier denitrification in the production of nitrous oxide revisited. Soil Biology & Biochemistry 123, A3-A16.
WRB, F., 2006. World reference base for soil resources 2006: A framework for international classification, correlation and communication. FAO, Rome.
Wu, X., Li, H., Rengel, Z., Whalley, W.R., Li, H., Zhang, F., Shen, J., Jin, K., 2022. Localized nutrient supply can facilitate root proliferation and increase nitrogen-use efficiency in compacted soil. Soil and Tillage Research 215, 105198.
Xin-sheng, N., ZHANG, H.-y., Ling-an, N., 2011. Crop straw resources and utilization in typical agricultural region of north China plain. Journal of Anhui Agricultural Science 39, 1710-1712.
Xue, Q., Li, J.s., Liu, L., 2014. Effect of Compaction Degree on Solidification Characteristics of Pb‐C ontaminated Soil Treated by Cement. CLEAN–Soil, Air, Water 42, 1126-1132.
Yang, P., Dong, W., Heinen, M., Qin, W., Oenema, O., 2022. Soil Compaction Prevention, Amelioration and Alleviation Measures Are Effective in Mechanized and Smallholder Agriculture: A Meta-Analysis. Land 11, 645.
Yang, Y., Li, M., Wu, J., Pan, X., Gao, C., Tang, D.W., 2021. Impact of Combining Long-Term Subsoiling and Organic Fertilizer on Soil Microbial Biomass Carbon and Nitrogen, Soil Enzyme Activity, and Water Use of Winter Wheat. Frontiers in Plant Science 12.

Yeomans, J.C., Bremner, J.M., 1988. A rapid and precise method for routine determination of organic carbon in soil. Communications in soil science and plant analysis 19, 1467-1476.

Yu, Y., Makowski, D., Stomph, T.J., van der Werf, W., 2016. Robust Increases of Land Equivalent Ratio with Temporal Niche Differentiation: A Meta‐Quantile Regression. Agronomy Journal 108, 2269-2279.

Yu, Y., Stomph, T.-J., Makowski, D., van der Werf, W., 2015. Temporal niche differentiation increases the land equivalent ratio of annual intercrops: a meta-analysis. Field Crops Research 184, 133-144.

Zhang, X., Shao, L., Sun, H., Chen, S., Wang, Y., 2012. Incorporation of soil bulk density in simulating root distribution of winter wheat and maize in two contrasting soils. Soil Science Society of America Journal 76, 638-647.

Zhou, L., Monreal, C.M., Xu, S., McLaughlin, N.B., Zhang, H., Hao, G., Liu, J., 2019. Effect of bentonite-humic acid application on the improvement of soil structure and maize yield in a sandy soil of a semi-arid region. Geoderma 338, 269-280.

Zhou, S.-L., Wu, Y.-C., Wang, Z.-M., Lu, L.-Q., Wang, R.-Z., 2008. The nitrate leached below maize root zone is available for deep-rooted wheat in winter wheat–summer maize rotation in the North China Plain. Environmental Pollution 152, 723-730.

Zibilske, L., Bradford, J., Smart, J., 2002. Conservation tillage induced changes in organic carbon, total nitrogen and available phosphorus in a semi-arid alkaline subtropical soil. Soil and Tillage Research 66, 153-163.

Zuber, S.M., Behnke, G.D., Nafziger, E.D., Villamil, M.B., 2015. Crop rotation and tillage effects on soil physical and chemical properties in Illinois. Agronomy Journal 107, 971-978.

Summary

Soil compaction is defined as the "densification of soil and the distortion of soil structure", which causes the deterioration or loss of one or more soil functions. Soil compaction may be caused by natural processes and factors and human activities. Soil compaction induced by human activities in agriculture and forestry, by inappropriate soil cultivation and heavy machinery, is especially a concern, as it increasingly impairs a range of soil functions and ecosystem services. It restricts root growth and nutrient uptake, and thereby crop productivity. It limits water infiltration in soil and affects the decomposition and transformation of organic matter and nutrients. Subsoil compaction is partly hidden, and compacted subsoils are not easily recognized and quantified, also because there is no common, routine monitoring of soil compaction in practice. This holds especially for the subsoil. Most common indicators for compacted soils are bulk density and soil penetration resistance, as these reflect the state of the soil. Common impact indicators are crop yield and water infiltration rate.

Various measures have been proposed and examined in the laboratory and in field experiments, including prevention measures (controlled traffic, no tillage, minimum tillage), amelioration measures (subsoiling and deep ploughing), and effect-alleviation measures (residue returning, controlled irrigation, manure application, crop rotation). Prevention is commonly preferred, also because the amelioration and alleviation measures have negative side-effects, but preventive measures are not easily implemented in practice in current socio-economic competitive conditions.

There is as yet no recent systematic analysis of the literature on the effects of the aforementioned measures in different cropping systems (e.g., mechanized agriculture and small-holder agriculture). Moreover, there is little information about within-field spatial variations in soil bulk density and spatial variations in soil functioning (i.e., crop productivity and transformation of nutrients). There is also a need for developing novel, high-precision methods for ameliorated compacted subsoil, without negative side-effects.

The general objective of my PhD thesis research was to increase the understanding of spatial variations in soil compaction in farmers' fields, and of the efficacy of measures aimed at the prevention, alleviation and remediation of soil compaction. The specific research objectives were:

i. to review the recent (from 2000) literature on measures aimed at the prevention, alleviation and remediation of soil compaction, and to examine possible difference between small-holder and mechanized agriculture;
ii. to examine the relationships between spatial variations in subsoil compaction and

spatial variations in soil properties, crop yield and nitrous oxide emissions;

iii. to examine the effects of four soil tillage practices on soil bulk density, soil carbon and nutrient sequestration and crop yield in a long-term field experiment;

iv. to develop and test a prototype measure for high-precision amelioration of compacted subsoil in small-holder agriculture and mechanized agriculture.

In my thesis research, I combined the use of literature review and meta-analysis, field experiments and laboratory measurements to explore the relationships between soil compaction and soil functioning in mechanised and small-holder farming systems. My thesis comprises 4 research Chapters, next to a General Introduction and General Discussion.

In Chapter 2, I present the results of a literature review and meta-analysis of the effects of soil compaction prevention, amelioration, and alleviation measures in mechanized and small-holder agriculture, using 712 observations on crop yield and soil bulk density/penetration from 57 studies published between 2000-2019/2020. Measures included deep ploughing, subsoiling, rotary tillage, minimum tillage, no tillage, improved drainage, growing deep-rooting crops, and soil organic amendments. Cereal crops (wheat, maize, rice, barley, and sorghum) were chosen as test crops. The effects of these measures on crop yield were quantitatively analysed, as well as the effects on soil physical properties (soil bulk density and soil penetration resistance). Mean effect sizes of crop yields were large for controlled traffic (38% in mechanized agriculture and 16% in small-holder farming systems) and irrigation (+51% in small-holder systems), modest for subsoiling, deep ploughing, and residue return (+10%), and negative for no-tillage (−6%). Crop residue mulching and manure application (alleviation measures) had a small effect. Mean effect sizes of soil bulk density were small (<10%), suggesting that bulk density is not a sensitive 'state' indicator. Mean effect sizes of penetration resistance were relatively large, but with large variations. The relatively large number of studies related to deep tillage in small-holder farming systems suggests that subsoil compaction is increasingly seen as a constraint to crop production in small-holder farming systems. No fundamental differences between mechanized and smallholder agriculture systems were found in the mean effect sizes of the prevention, amelioration, and impact alleviation measures. Measures that prevent soil compaction are commonly preferred, but amelioration and alleviation are often equally needed and effective, depending on site-specific conditions. A toolbox of soil compaction prevention, amelioration, and alleviation measures was proposed, targeted to farm and field-specific conditions.

In Chapter 3, I examined spatial variations of soil properties and bulk density in farmers' fields in the Hoeksche Waard, Netherland. Four fields were selected, with areas ranging from 8 to 20 ha. Both topsoil and subsoil samples were measured for soil physical characteristics (soil texture, bulk density, pore size distribution, penetration resistance), soil chemical characteristics (pH, organic carbon, extractable nutrients) and soil biological characteristics (respiration, N_2O production). Corresponding crop yields were recorded by harvesters equipped with GPS and yield recorders. The Inverse Distance Weighted interpolation tool of ArcGIS, the semi-variogram method of GS+ software, and linear regression models were used to analyse the spatial dependence and spatial distribution coefficients of crop yields and soil properties, as well as the relationships between spatial variations in subsoil compaction and spatial variations in crop yields. These tools were effective for characterizing spatial variations in soil properties, soil processes and crop yields. Spatial variations in both topsoil and subsoil bulk density were negatively related to spatial variations in the potential emissions of CO_2 and N_2O; emissions of N_2O increased with an increase in soil bulk density. Spatial variations in wheat yield were not related to spatial variations in soil bulk density. Potential N_2O emissions (and the ratio of potential CO_2 emissions to potential N_2O emissions) were considered more sensitive for assessing the effect of increases in soil bulk density on soil functioning than wheat yields.

In Chapter 4, I present the results of a long-term (18 years) field experiment conducted in a winter wheat-summer maize double cropping system in Luancheng, China, in which I was involved during early stages as MSc student and in later stages as a PhD student. Four tillage treatments were included in the experiment, i.e., moldboard ploughing with crop residues removed (CK); moldboard ploughing with crop residue returned (CT); rotary tillage with residue returned (RT); and no tillage (NT) with residue returned. Effects of different tillage and residue returning treatments on crop yields, soil bulk density and carbon, nitrogen and phosphorus sequestration in soil were analysed. The average winter wheat yields were 18% lower under no tillage (NT) and 6% lower under reduced tillage (RT) than under conventional moldboard plowing (CT) during 2005 to 2018. Initially, NT and RT treatments rapidly increased the content of SOC in the soil surface (0-5 cm) layers, but after 17 years the SOC content was higher in the CT treatment than in the NT and RT treatments in the top 20 cm of soil. Therefore, no tillage and reduced tillage decreased both wheat yields and soil C sequestration over time compared to the conventional tillage practice. Tillage treatments did not significantly affect maize yields. The differential accumulations of available soil nutrients, together with a relatively high bulk density of the subsoil, may affect the nutrition of crops in the long-term, and may contribute to the relatively low winter wheat yield in the NT treatment in the double cropping system. Therefore, the dynamics of soil nutrients in different soil layers must be considered in studies evaluating the effects of tillage on soil carbon sequestration and crop yield.

In Chapter 5, I present the results of a novel high-precision bore-hole method for ameliorating compacted subsoil. Prototypes were tested in four field experiments, two of which were conducted in Luancheng, China, and two in Odiliapeel, The Netherlands. Maize and sorghum were used as test crops in Odiliapeel and maize in Luancheng. Bore-holes were made by hand auger and were positioned below the plant holes of the row crops. Different bore-hole diameter (range 6-10 cm) and depth (30 vs 60 cm) were tested. The bore-hole treatments were combined with and without manure amendments. The bore-hole method was effective in enhancing maize yields by up to 30% in the two experiments in Luancheng and in one experimental treatment in Odiliapeel. The compacted soil layer was at 15-30 cm in Luancheng (China, with small-holder agriculture and small machines) and at 30-50 cm in Odiliapeel (Netherland, where contractors often use large machines with high axle loads), and this difference likely contributed to the greater effects of the bore-hole method in Luancheng than in Odiliapeel. No clear differences were found for the bore-hole diameter in the range of 6 to 10 cm. Also, the yield enhancing effect was similar in treatments with 30 cm and 60 cm deep bore-holes in Luancheng. Roots grew preferentially in the bore-holes, but no statistically significant differences in root weight were found between treatments for depths of 0-20, 20-40 and 40-60 cm. Sorghum did not respond to the bore-hole treatments.

The main conclusions of my PhD thesis are as follows:

- There is no fundamental differences between mechanized and small-holder agriculture in the mean effect sizes of the prevention, amelioration, and impact alleviation measures. Prevention measures were more studied in mechanized agriculture, and amelioration and alleviation measures more in small-holder agriculture. Measures that prevent soil compaction are commonly preferred, but amelioration and alleviation are often equally needed and effective, depending on site-specific conditions.
- Within-field spatial variations in subsoil bulk density were successfully related to spatial variations in potential CO_2 and N_2O emissions. The ratio of CO_2 emissions to N_2O emissions had a much greater response to spatial variations in soil bulk density than wheat yield. Our study suggests that N_2O emission factors may depend on (sub)soil bulk density, and bulk density should therefore be included in assessment studies of N_2O emissions from land.
- No tillage and reduced tillage decreased both wheat yields and soil C sequestration over time. Conventional tillage with crop residue return was the most robust tillage method in terms of crop yields and soil C sequestration in the long-term field experiments.
- The bore-hole method was effective in enhancing the yield of maize grown on compacted subsoils, but further tests are needed to explore the potentials of the proto-type method in practice and for a better understanding of the cause-effect relationships.
- A toolbox of soil compaction prevention, amelioration and alleviation measures was proposed.

Acknowledgements

This thesis is not complete without expressing my sincere gratitude to people who helped me during my PhD journey.

Firstly, I would like to express my sincere gratitude to my promoter and supervisor Dr. Prof. Oene Oenema for the continuous support of my PhD journey, for his patience, motivation, and immense knowledge. I benefited greatly from his professional supervision and critical commenting. I could not have imagined having a better advisor and mentor for my PhD journey. Thank you for your enthusiasm, and supports for being such a smart, funny and inspiring person. Getting to know you was a life-changing moment.

Second, I would like to give special thanks to my co-supervisor, Dr. Prof. Chunsheng Hu, who is also my master's supervisor, for his unreserved supports to my study. I really appreciate your supervision and guidance during both my MSc study and my PhD study. I feel very lucky and I'm proud of being your student.

I would like to express my grate appreciation to Chinese scholarship Council (CSC), who supported me 4 years living stipend. I even couldn't start my PhD journey without you.

Besides, I would like to than many important people who helped me during my PhD journey. Marnella van der Tol, secretary of Soil Biology Group, you are the first person who helped me since I arrived Wageningen. Thank you so much for your continuous help and encourages. Your enthusiasm inspires me each day I see you. Dr. Arjan Reijneved, who is the first PhD student of my supervisor Oene Oenema, offered plenty of help in my sampling test and thesis writing. Popko Bolhuis and Edward, technicians of Soil Biology group, many thanks to you two for your hard work and sincere help during the field experiment in Hoeksche Waard and Odiliapeel. I couldn't finish my experiments without you two. So do the help of Junqi Yang in Luancheng experimental station, China.

Many thanks to Wei Qin, Zhaohai Bai, Yong Hou, Jingmeng Wang, Qian Liu and Mengchu Guo, for your accompaniment and great supports, which made my life in Wageningen an extraordinary journey.

Special thanks to Dr. Prof. Wenxu Dong, who encourages me not only in my study, but also in daily life. My PhD journey would not have gone smoothly and successfully without your help. Also many thanks to Dr. Prof. Lin Ma, who supported part of my experiment expenses in China.

I would like to express my deepest gratitude to my parents and my husband Jian Zhao for their love and support. Their understanding and encouragements helped me to move forward. These supports are priceless and immeasurable. I'm nothing without my family.

Thanks to all of you!
Peipei Yang,
2022

About the author

Peipei Yang was born on 9 Dec, 1986 in Shijiazhuang, China. In 2004, she graduated from Xinji High School of Hebei. After that, she studied Resource and Environmental Science in the College of Natural Resource and Environment, Northwest A&F University, China. She received the Bachelor degree in 2008; the thesis was entitled 'The Effects of Different Nitrogen Application Rates on N_2O Emissions from Winter-wheat Field'. She continued her study as a master student in the Centre for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences (IGDB, CAS), supervised by Prof. Chunsheng Hu. She received the Master of Science degree in Ecology in 2011; the thesis was entitled 'Effects of experimental warming & N-fertilization on soil N_2O & CO_2 emission in North China Plain'.

In 2015, she became a PhD candidate in the Soil Quality Group, Wageningen University, the Netherlands. She was supervised by Prof. Oene Oenema and Prof. Chunsheng Hu. Her PhD dissertation is entitled 'Exploring relationships between soil compaction, amelioration and functioning. Her study was funded by the State Scholarship Fund (Chinese Scholarship Council) and by the EU project SoilCare.

Authorship statement

PhD candidate's name: Peipei Yang
First promotor: Oene Oenema
Title of PhD thesis: Exploring relationships between soil compaction, amelioration and functioning
Date of public defense: Nov 1, 2022

Chapter 1 *General introduction.* The general research questions were proposed by my promotor. I delineated the research questions, described how it fits in the current scientific literature and described its potential social impact. I revised the text two times, after comments of my promotor.

Chapter 2 *Soil compaction prevention, amelioration and alleviation measures are effective in mechanized and smallholder agriculture: a meta-analysis.* The research described in this chapter was part of the EU funded project SoilCare ("Soil care for profitable and sustainable crop production in Europe"). The initial research questions were based on the objective of the project SoilCare, but were amended during the course of the study. I proposed the methodology with the help of my promoter. I did the literature review, data analysis, and wrote the draft manuscript. I revised the text five times, following comments of my promotor and other co-authors.

Chapter 3 *Within-field spatial variations in subsoil bulk density related to crop yield and potential CO_2 and N_2O emissions.* This chapter was based on a cooperation between farmers, WUR staff, and Eurofins Agro company. I contributed to defining the research question, proposed the methodology and the experimental design with the help of my promoter. I did the field sampling and laboratory measurements with the help of technicians. I did the data analysis and wrote the draft manuscript. I revised the five times, following comments of my promotor and co-authors.

Chapter 4 *Responses of cereal yields and soil carbon sequestration to four long-term tillage practices in the North China Plain.* This chapter is part of a long-term field experiment, in which I was involved at the start during the periode 2008-2011, when I was a MSc student, and again during the period 2019 to 2021 as PhD student. I analyzed the data and wrote the first draft together with the first authors. We revised the text four times, following comments of my promotor, co-promoter and co-authors.

Chapter 5 *A bore-hole method for remediating compacted subsoils increased maize yield - prototype field tests.* I proposed the research question and methodology with the help of my promoter. I did the field work and laboratory measurements with the help of technicians. I did the data analysis and wrote the draft manuscript. I revised the text five times, following comments of my promotor and co-authors.

Chapter 6 *General discussion*. I wrote the first draft of the text after a discussion with my promotors on the subjects and arguments to be included. I revised the text once, after comments of my promotor and co-promotor.

2022

Signature PhD candidate: Peipei Yang

Signature promotor for agreement Oene Oenema

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Review of long-term soil management practices and crop yield

Writing of project proposal (4.5 ECTS)

- Exploring relationships between soil compaction and soil functioning

Post-graduate courses (4.3 ECTS)

- Geostatistics; PE&RC (2015)
- Introduction to R for statistical analysis; PE&RC (2015)
- mixed linear models; PE&RC (2015)
- Meta-analysis; PE&RC (2016)
- R&big data; PE&RC (2017)

Competence strengthening / skills courses (2.7 ECTS)

- The essentials of scientific writing and presenting; WGS (2015)
- Project and time management; WGS (2016)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.8 ECTS)

- PE&RC First year's weekend (2015)
- PE&RC Last year's weekend (2018)

Discussion groups / local seminars or scientific meetings (6 ECTS)

- R User meetings (2015-2019)

International symposia, workshops and conferences (5 ECTS)

- Wageningen soil conference (2015, 2017)

BSc / MSc thesis supervision (3 ECTS)

- Experiment on shrink and swell ability of bentonite on small scale