Techniques for the recovery of compacted soils in Europe

Guido Bakema, Emmanuel Arthur, Derk van Balen

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

Techniques for the recovery of compacted soils in Europe

Guido Bakema[1], Emmanuel Arthur[2], Derk van Balen[3]

1 Wageningen Environmental Research, The Netherlands

2 Aarhus University Department of Agroecology, Denmark

3 Wageningen Plant Research, The Netherlands

This research was funded by the Dutch Ministry of Agriculture, Nature and Food Quality and by the European Union's Horizon 2020 research and innovation programme as part of the EJPSoil project, grant agreement No. 862695.

Wageningen Environmental Research
Wageningen, May 2023

Reviewed by:
Simone Verzandvoort (WENR) and Florian Schneider (Thünen-Unstitut)

Approved for publication:
Mirjam Hack-ten Broeke, team leader of Soil, water and land use (WENR)

Report 3260
ISSN 1566-7197

EJP SOIL has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695

Bakema, G, Arthur, E. and D. van Balen, 2023. *Techniques for the recovery of compacted soils in Europe.* Wageningen, Wageningen Environmental Research, Report 3260. 52 pp.; 22 fig.; 3 tab.; 91 ref.

Bodemverdichting als gevolg van landbouwmachines is een van de grootste bedreigingen voor de productiviteit van de bodem en het ecologisch en hydrologisch functioneren van de bodem. In dit onderzoek, dat deel uitmaakt van het EJPSOIL SOILCOMPAC-project, is een uitgebreid literatuuronderzoek naar herstelmaatregelen uitgevoerd. Daarnaast is een overzicht gemaakt van oude en lopende experimenten met herstelmethoden in verschillende landen. Het overzicht omvat mechanische (grondbewerking), biologische (diep wortelende gewassen) en natuurlijke methoden (bevriezen en zwellen). Dit onderzoek is toegespitst op de verdichte ondergrond onder de ploegzool (25-50 cm m-mv.). Dit betekent dat de focus hiermee ligt op akkerbouw hoewel de meeste herstelmaatregelen ook kunnen worden toegepast op grasland.
In het verleden werd vaak gekozen voor het mechanisch openbreken van de verdichte ondergrond. Dit leverde op korte termijn verbetering op, maar een aantal jaren later trad opnieuw verdichting op. Het belangrijkste nadeel van mechanische methoden is dat vaak de volledige bodemstructuur wordt verstoord, waardoor de mechanische sterkte en het vochtleverend vermogen sterk verminderen. Het meest veelbelovend is het gebruik van diepwortelende planten ook wel biosubsoilers genoemd.

In een korte video zijn de belangrijkste bevindingen van het rapport samengevat. 0048c8b2-a49f-494c-8bc3-0487d4317d9d-mp4_720p (2).mp4

Soil compaction due to agricultural vehicle traffic is recognized as one of the major threats to soil productivity, and soil ecological and hydrological functioning. In this research, which is part of the EJP SOIL SoilCompaC project, an extensive literature review on recovery techniques was conducted combined with data from current recovery field experiments. An overview was made of past and running experiments on recovery methods in different countries to characterize the rate of recovery by different processes and the relative importance of the recovery mechanisms across pedo-climatic zones. The review includes mechanical (tillage), biological ("biosubsoiling") and natural methods. The focus of this research was made on the compacted subsoil below the plough sole (25-50 cm b.s.). This means that the focus with this is on arable farming however most of the recovery techniques can also be applied to grassland.
In the past, the choice was often made to mechanically crack the compacted soil. This resulted in short-term improvement but recompaction occurred several years later. The main disadvantage of mechanical methods is that often the complete soil structure is disturbed, which strongly reduces the mechanical strength and moisture delivery capacity. Most promising for the long-term melioration of compacted arable land is the use of deep-rooting plants: biosubsoilers.

A short video summarizes the main conclusions 0048c8b2-a49f-494c-8bc3-0487d4317d9d-mp4_720p (2).mp4

Keywords: Soil compaction, recovery of compacted soils, biosubsoiling, freezing/thawing, subsoiling

The pdf file is free of charge and can be downloaded at https://doi.org/10.18174/629799 or via the website www.wur.nl/environmental-research (scroll down to Publications – Wageningen Environmental Research reports). Wageningen Environmental Research does not deliver printed versions of the Wageningen Environmental Research reports.

In 2003 Wageningen Environmental Research implemented the ISO 9001 certified quality management system. Since 2006 Wageningen Environmental Research has been working with the ISO 14001 certified environmental care system. By implementing the ISO 26000 guideline, Wageningen Environmental Research can manage and deliver its social responsibility.

Wageningen Environmental Research Report 3260 | ISSN 1566-7197

Photo cover: Sorghum as a bisosubsoiler (Guido Bakema, 2022)

Contents

Verification

Report: 3260
Project number: 520044137

Wageningen Environmental Research (WENR) values the quality of our end products greatly. A review of the reports on scientific quality by a reviewer is a standard part of our quality policy.

Approved reviewer who stated the appraisal,

position: researcher

name: Simone Verzandvoort

date: 13-03-2023

position: researcher (Thünen-Unstitut)

name: Florian Schneider

date: 30-03-2023

Approved team leader responsible for the contents,

name: Mirjam Hack-ten Broeke

date: 15-05-2023

Preface

This research on soil compaction recovery is part of the EJP SOIL project SoilCompaC. SoilCompaC involves 12 countries across Europe, which makes it possible to consider a wide range of European pedo-climate zones across climate gradients and different farm structures and cropping systems. SoilCompaC consists of three work packages that focus on compaction detection and recovery (WP1), compaction risk assessment (WP2), and quantification of compaction impacts on soil functions (WP3), under current and future climate.

This research was (partly) subsidised by the Dutch Ministry of Agriculture, Nature and Food Quality and EJP SOIL.

Summary

Soil compaction due to agricultural vehicle traffic is recognized as one of the major threats to soil productivity, and soil ecological and hydrological functioning. The size and weight of agricultural machinery have significantly increased during the last decades which is likely to have increased compaction levels. The recently published report of the mission board for soil health and food, "Caring for soil is caring for life" (European Commission, 2020) estimates that the area of land failing soil health due to compaction is 23-33% (7% of which outside agricultural area).

Preventing soil compaction is important because the effects of structural decay can affect yields for decades and the decreased infiltration and storage capacity. Once a soil becomes compacted, there are several techniques to solve this. However, the question is which techniques are available, how long they are effective and under what conditions they are best used.

In this research, which is part of the EJP SOIL SOILCOMPAC project, an extensive literature review was conducted and combined with data from current recovery field experiments. An overview is made of past and running experiments on recovery methods in different countries to characterize the rate of recovery by different processes and the relative importance of the recovery mechanisms across pedo-climatic zones. The review includes mechanical (tillage), biological ("biosubsoiling") and natural (soil physical processes) methods. The research was made on the compacted subsoil below the plough layer (25-50 cm b.s.). This means that the focus is on arable farming however most of the recovery techniques can also be applied to grassland.

The main conclusions from this research are as follows:

Biosubsoiling seems preferable to mechanical recovery
In the past, the choice was often made to perform mechanical cracking of the compacted soil. This resulted in short-term improvement but recompaction occurred several years later. The main disadvantage of most mechanical methods is that often the complete soil structure is disturbed, which strongly reduces the mechanical strength and moisture delivery capacity. The mechanical method of subsoiling is useful for certain soils if executed with the right equipment and under not-too-wet conditions. However, it's loosening effect will only be preserved if afterwards traffic loads are strongly reduced and cover crops with high belowground biomass are used.

However, to prevent disruption of natural structures and fast recompaction, it is better to choose more natural recovery methods. For especially some of the heavier soils, dehydration and freezing can restore the soil structure but the effect on the subsoil (> 25 cm bs.) seems generally limited. The most promising technique is the use of deep-rooting plants: biosubsoilers. This is because they have an effect right down to the subsoil and also have a limited negative influence on the topsoil. However, more research is needed into which deep-rooting crops are most effective under which soil conditions and how they can be incorporated into the cropping system.

Soils with high clay content have the greatest potential for recovery
Overall, it can be said that soils with a high clay content have the greatest potential for recovery. This applies to both the more natural solution and the mechanical solutions. For the latter, it must take place under conditions that are not too wet. For soils with low clay content, swelling/shrinking and freezing/thawing are processes that contribute little or nothing to eliminating soil compaction. Subsoiling is possible for these soils but there is a high risk of re-compaction for soils with a high silt fraction. Biosubsoiling seems suitable for most soils, but the effectiveness will depend heavily on soil moisture conditions.

All recovery techniques have a low recovery rate
Complete recovery of soil properties to levels prior to soil compaction is rarely observed in the experiments (n= 14) studied. In 80% of the experiments, no more than 50% recovery was found. Only in an exceptional situation was a complete recovery of soil functions found.

Efficiency of recovery depends on soil texture and climate conditions
Climate conditions can exclude recovery techniques. A continental climate with freeze and thaw on a soil with >20% clay is suitable for natural recovery by swelling and shrinking of the soil. In this case, biosubsoiling can only be useful when the growing period of a crop or cover crop is long enough to develop roots in deeper soil layers when soil moisture is restored in late summer. Dry hot summers and wet warm winters on soil < 20% clay cannot restore soil compaction by swelling and shrinking. In this case, winter- and cover crops can 'bio-till' the soil. Ploughing or killing of the cover crops must be postponed to spring, to take maximum advantage of the root growth. Year-round precipitation is ideal for biotillage on sandy and clay soil. On clay soil >20% is a combination with swelling and shrinking of the soil possible.

More research is needed on deep-rooting crops.
More research is needed into the use of deep-rooting crops in combination with subsoiling and as a biosubsoiler. Important questions here include (a) which crops are most effective in cracking the soil and remaining soil structure, (b) what are the soil conditions (physical and chemical) under which they grow best, (c) is it enough to grow the crop for one winter season or should the crop be allowed to grow for several seasons.

A short video summarizes the main conclusions 0048c8b2-a49f-494c-8bc3-0487d4317d9d-mp4_720p (2).mp4

1 Introduction

1.1 Soil compaction a threat to agricultural soils in the EU

Soil compaction due to agricultural vehicle traffic is recognized as one of the major threats to soil productivity and soil ecological and hydrological functioning (FAO and ITPS, 2015). The EJP Soil stocktake among stakeholders identified avoiding and alleviating soil compaction as a top priority (Munkholm and Zechmeister-Boltenstern, 2021). Many studies have documented the negative consequences of soil compaction, which include adverse effects on agricultural production, water flow and storage, aeration, and nutrient cycling (see e.g. reviews by Hamza and Andersson, 2005; Hu et al., 2021). In addition, prevention of and restoration from soil compaction is the 6th objective defined in the new Soil Mission implementation plan of the European Union (https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/missions-horizon-europe/soil-health-and-food_en).

The already acute threat of soil compaction is expected to aggravate in the future due to the continued trend towards larger and heavier agricultural machinery (Schjønning et al., 2015; Keller et al., 2019). Moreover, climate change with projected increases in the occurrence and severity of extreme weather events, such as droughts and floods, almost everywhere in Europe (IPCC, 2013), may further aggravate the negative consequences of compaction.

1.2 Recovery of soil compaction within EJP Soil SoilCompaC

Despite the well-documented adverse effects of soil compaction on key soil functions, there is little data on the spatial extent, distribution and severity of soil compaction. Typically cited figures of compaction-affected land area (e.g. Oldeman et al., 1991) are uncertain and outdated. The size and weight of agricultural machinery have significantly increased during the last decades (Keller, 2022), which is likely to have increased compaction levels. The recently published report of the mission board for soil health and food, “Caring for soil is caring for life” (European Commission, 2020) estimates that the area of land failing soil health due to compaction is 23-33% (7% of which outside agricultural area).

Novel techniques such as remote sensing may offer new ways for quantifying compaction at spatial scales from field to region. Better knowledge of the spatial extent and distribution of soil compaction across Europe is needed for better guidance in sustainable soil management and alleviation of compaction damage. Moreover, knowledge of the extent and severity of compaction would be valuable information to better estimate the ecological and economic costs of soil compaction. It can also help to better understand the complex interactions between soil management, undesired consequences of soil management (i.e., soil compaction), and ecosystem services including soil productivity, climate regulation and flood regulation.

SoilCompaC as part of the EJP Soil project has three work packages: detection of compaction and alleviation (WP1), compaction risk assessment (WP2), and quantification of compaction impacts on soil functions (WP3), under current and future climate. SoilCompaC involves 12 countries across Europe, which makes it possible to consider a wide range of European environmental zones across climate gradients and different farm structures and cropping systems.

1.3 Project aims

Task 1.3 within EJP SOIL SoilCompaC is about the recovery of soil to its previous level of ecosystem services provision after traffic-induced compaction. The recovery process may be induced naturally by mechanisms such as freeze-thaw (Jabro et al., 2014), shrink-swell (Horn and Schmucker, 2005), and wet-dry cycles (Sarmah et al., 1996), by mechanical operations such as subsoiling (e.g. Schneider et al., 2017), or by biological processes such as root penetration of compacted layers (e.g. Pulido-Moncada et al., 2021).

In this task, we will conduct an extensive literature review of techniques (Chapter 2) on the recovery of arable soils from compaction, including a review of data from current field experiments. We will get an overview of past and running experiments on recovery methods in different countries (Chapter 3) (i.e., different soils and different climates) to characterise the rate of recovery by natural processes and the relative importance of the recovery mechanisms across pedo-climatic zones (Chapter 4). The review will include mechanical (tillage), biological ("biosubsoiling") and natural techniques. The different techniques will be technically evaluated and also the applicability for different pedo-climate conditions will be judged.

The focus of this report is on the compacted subsoil in agricultural land below the plough sole (25-50 cm b.s.) This means that the focus is on arable farming however most of the recovery techniques can also be applied to grassland.

2 Literature review on recovery from soil compaction

2.1 Natural recovery

Natural processes such as swelling and shrinking and freezing and thawing can partially resolve subsoil compaction. In general, much research has been done on these processes for the topsoil but the number of studies for the subsoil is limited. What is known is that the natural recovery of the subsoil is a process of many years. This is based in part on long-term trials from the 1980s that looked at the long-term yield reduction after a one-time compaction event. Håkansson and Reeder (1994) concluded that after four to five years the effect of subsoil compaction on crop yield was a reduction of about 5% and that after ten years and the following years it was still 2.5% (**Fout! Verwijzingsbron niet gevonden.**). It should be borne in mind that in the experiments all these years the wheel loads remained below 25 kN. In Finland, the one-time compacted plots were followed for a long time and Alakukku (1996) still found lower yields in the compacted plots after 17 years.

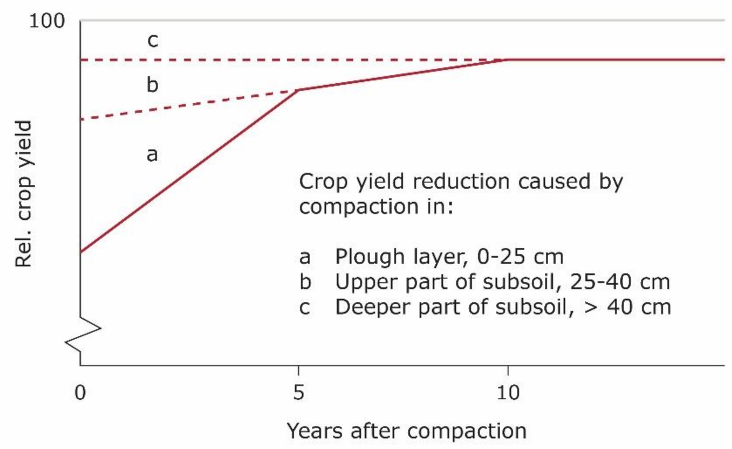

Figure 2-1 *Effect of topsoil and subsoil compaction on crop yield. Schematized result of an extensive international series of field trials in which a single plot was wheel-to-wheel driven four times with wheel loads of 5 tons. In subsequent years, only light wheel loads were driven to study the recovery of the soil. A distinction was made between the recovery of the top soil or plough layer (a), the upper subsoil (b) and the deeper subsoil (c). (After Håkansson and Reeder (1994)).*

2.1.1 Swelling and shrinking

The process
Clay soils distinguish themselves from other soils by the presence of certain amounts of clay minerals like kaolinite, illite and montmorillonite. Clay minerals occur in plate-shaped crystals. These crystals are built up of small platelets, consisting of siliconoxides and aluminium hydroxides. The thickness of each platelet is about 5-10 Â. The number of platelets within one clay crystal depends on the configuration of the silicionoxides and the aluminium hydroxides in the platelet but may vary from 1 (Na-montmorillonite) to almost infinite (Kaolinite) (Bronswijk, 1991). Due to the special structure of clay minerals, platelets or packets of platelets are surrounded by water layers. Upon drying, the platelets approach each other (Bronswijk, 1991) (Figure 2-2).

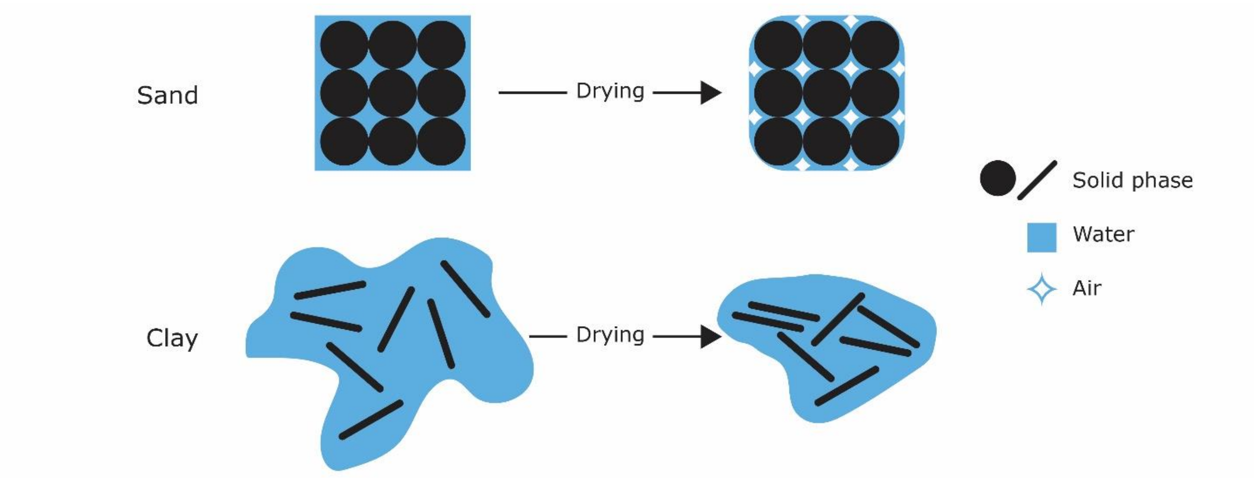

Figure 2-2 *Schematic representation of the process of drying and air entry in sandy soils and clay soils (After, Bronswijk, 1991).*

The drying out of the clay soil results in cracks and subsidence. When clay soil is hydrated, the cracks swell partially or completely again and the ground level rises. The incomplete swelling of the clay after dehydration, which prevents the cracks from closing, is called irreversible shrinkage. The relationship between moisture content changes and volume changes of a clay soil can be represented by the Soil Shrinkage Characteristic Curve (SSCC) (Figure 2-3). In shrinkage, four phases are distinguished from wet to dry: structural shrinkage, normal shrinkage, residual shrinkage and zero shrinkage. In structural shrinkage, the moisture content decreases without decreasing the volume of the soil. In the phase of normal shrinkage, the volume of water and volume of soil decreases equally with the aggregates remaining fully saturated and only the shrinkage cracks (macropores) containing air. In the phases thereafter, air also enters the aggregates.

The degree of normal shrinkage depends greatly on the clay content. The heavier the clay the smaller the pores and the larger the shrinkage. In some heavy clay soils, only normal shrinkage occurs, which means that the soil aggregates are saturated throughout the year (Van den Akker et al., 2013).

Besides the magnitude of volume changes upon wetting and drying, which is described by the SSCC, the geometry of swelling and shrinking is of equal importance for modelling water transport in swelling and shrinking soil.

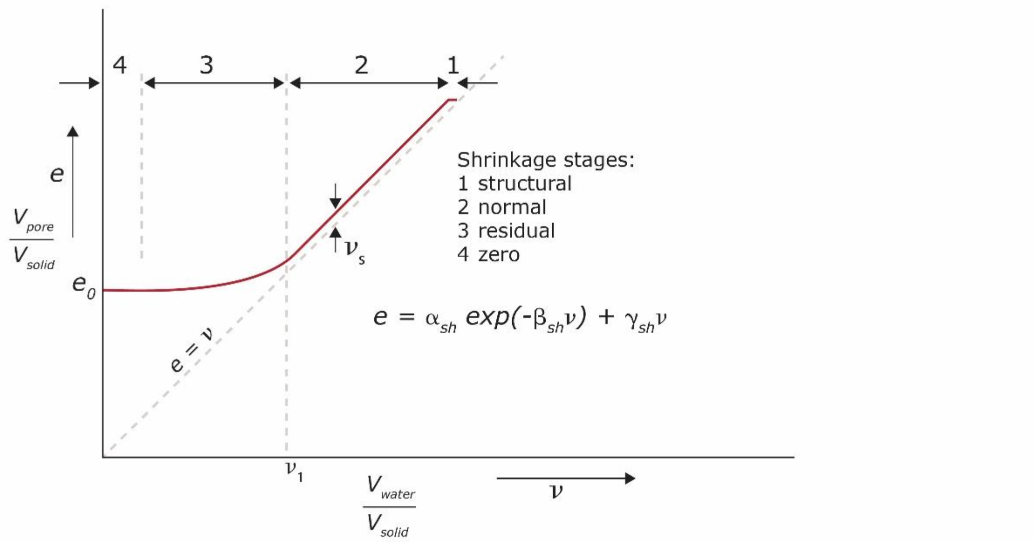

Figure 2-3 *Soil Shrinkage Characteristic Curve (SSCC) of a clay soil V_{pore} = poriënvolume, V_{solid} = volume solids, V_{water} = volume water (After Kim et al. 1992).*

The geometry determines to what extent a volume decrease in the soil matrix becomes visible as subsidence or as crack formation. At the top of the soil profile, the soil is usually drier and therefore stronger and stiffer than at greater depths. In addition, at the top of the soil profile, the load of overlying soil is not present or is present to a minor extent. As a result, shrinkage cracks will not be closed. The shrinkage is therefore isotropic at the top of the soil profile (equal in all 3 dimensions) and causes subsidence and cracking in equal measure. Deeper in the soil profile, the cracks are compressed by the overlying weight of the soil, so the entire volume of shrinkage at that depth is converted into soil subsidence at the surface.

Whether and how much a soil or aggregate shrinks (swells) due to withdrawal (or addition) of water depends on:

- The amount of water that can be extracted from the aggregate by the plant. A soil can be characterized in this respect by its water retention characteristic which gives the relationship between soil water potential (pressure head) and moisture content.
- The amount of water that can be absorbed in the aggregate by precipitation or by capillary water from deeper layers.
- The shrinkage (swelling) properties of the soil as shown in the shrinkage characteristic.

The combination of water retention characteristic and shrinkage characteristic follows the distribution of relative volume at different soil water potentials (Figure 2-4). The geometry factor (1: for anisotropic and 3: for isotropic) then determines the distribution of shrinkage across cracks or subsidence (Rijnierse, 1983).

Swelling versus shrinkage

Most studies of shrinkage and swelling behavior focus on the shrinkage process. This means that relatively little is known about the swelling process. It is known that peat and some clay soils in particular can be strongly hydrophobic (water-repellent) (Dekker and Ritsema, 1996 and Hoekstra et al., 2021). Before precipitation enters the aggregate, this can cause a delayed uptake of precipitation water and thus greater drainage of water through the shrinkage cracks to the subsurface. Drying of aggregates can thus occur from the inside through water uptake by roots while hydration will occur from the outside through precipitation.

This difference in processes during drying and wetting will lead to different behavior in shrinkage and swelling conditions.

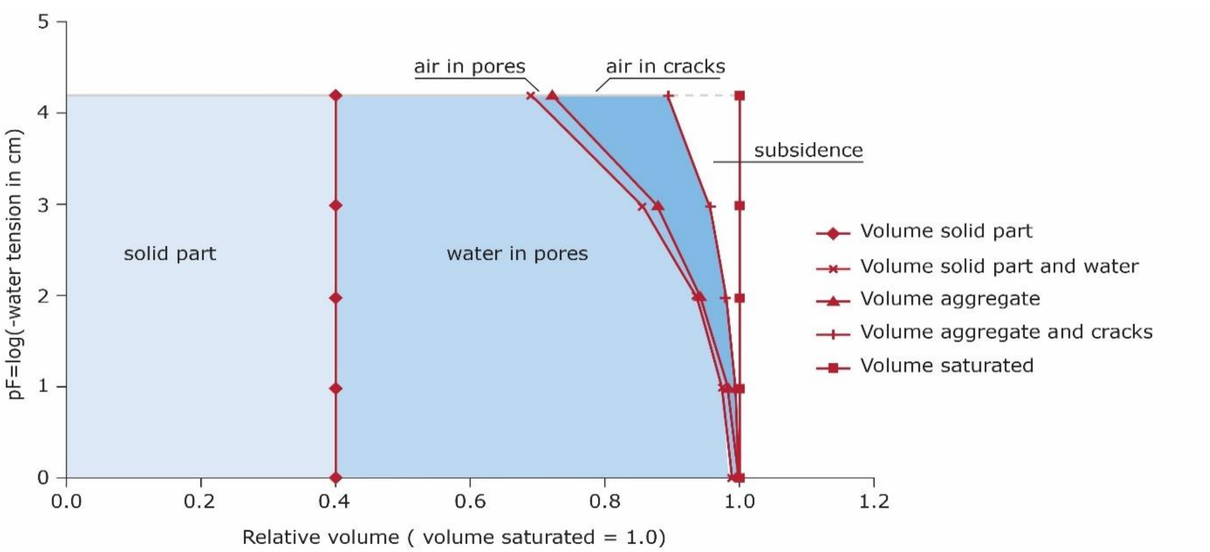

Figure 2-4 *Distribution of the relative volume in solids, water and air in relation to the soil water potential of a very heavy clay from Bruchem (NL) (After Van den Akker et al., 2013).*

Dexter (1991) also sees a big difference in the speed at which shrinkage cracks close again. In some soils, this occurs almost immediately while there are soils that take days or weeks for the cracks to close. He also sees a difference between cracks and biopores such as tunnels made by earthworms. When swelling causes the cracks to close, the biopores can remain open and thus provide space for plant roots.

Research on young Dutch clay soils (Flevoland) shows that shrinkage cracks can be found up to 1.2 m -mv and that they only close again in early spring (Figure 2-5). (Van den Akker et al., 2011).

Figure 2-5 *Soil profile with deep shrinkage cracks (Flevoland the Netherlands. In the upper 40 cm, the cracks disappeared due to tillage (Van den Akker et al., 2011).*

Experiments with swelling and shrinking

Much research has been done into the shrinking behavior of clay and peat soils. The influence of clay content, the number of dry/wet cycles, land use and organic matter content has been studied (Bronswijk 1991, Cornelis et al., 2006 and Dörner et al. 2009). In addition, these authors also experimented with various methods to measure the SSCC curve in the laboratory. The number of experiments on swelling soils is limited.

Most studies on the influence of swelling and shrinking on improving soil structure relate to tilled topsoil, where dry-wet treatments increase the volume and permeability of macropores (Grant et al., (1995), Pillai-McGarry et al. (1990) and Chinn et al. (2008)) This effect is commonly referred to as self-mulching: "the behavior in clay soils refers to the peculiar natural ability of such soils to generate a mulch of fine aggregates (<5mm) in the immediate surface after only a few cycles of wetting and drying" (McKenzie et al., (2002).

Studies on subsoils and soils in undisturbed (uncompacted) conditions are scarce (Schjonning et al. 2017). A number of studies have made in situ measurements of the subsoil. Dörner et al. (2009) found a significant difference in the volume of macropores in the soil for volcanic soils covered with native forest or pasture.

They concluded that management or climate systems were responsible for the significant increase in coarse pore volume. Liu et al. (2016) found a decrease in the bulk density of the upper soil for a light loam in northern China due to drying and wetting. Schjonning et al. (2017) investigated both freeze/thaw and swelling/shrinking. They found that dry-wet treatment was significantly more effective than freeze/thaw for improving soil structure. The improvement was found particularly in increasing the volume of the large pores and less in reducing the bulk density. De Leeuw (2009) conducted several field and lab experiments on compacted Dutch clay and sandy soils. For the clay soils, although not entirely unambiguous, an improvement in saturated permeability after shrinkage and swelling was found; the effect was not demonstrated for the silt soils.

Optimizing the effectiveness of swelling and shrinking
Research on clay topsoils in particular shows that swelling and shrinking can improve the structure. This effect is also observed for subsoils, although it is not always unambiguous because several processes can be responsible for the improvement. Furthermore, it becomes clear that the swelling/shrinkage process is highly dynamic, so it is not easy to demonstrate an improvement in soil structure as a result of swelling and shrinking.

The magnitude of the shrinkage/swelling process is determined by the type of clay, the clay content and the extent to which the clay can dry out sufficiently to create cracks (Bronswijk, 1991). Furthermore, the effect of the shrinkage/swelling process is influenced by tillage and compaction by heavy machinery, which reduces part of the structural improvement. In the Netherlands, the limit above which structural recovery through shrinkage can occur is generally set at a clay content of 17.5%. This means that the natural recovery capacity of sand and silty soils through this mechanism is very limited. Compared to other European clay soils, Dutch clay soils (relatively young soils) have a strong swelling and shrinking capacity in relation to other clay soils (Bronswijk, 1991).

Bronswijk's (1991) research also shows the importance of good drainage. On improving drainage, shrinkage cracks are found at greater depth (30-70 cm -mv) and in larger numbers (up to 50% increase). Withdrawal of water by the roots is the best way to dry the soil to a large depth. This gives shrinkage and biological processes the opportunity to restore the soil structure. Thus, deep and good rooting is essential for structure restoration by soil physical and biological restoration processes, and vice versa, good structure is essential for deep rooting. This reciprocal dependence means that the deeper the soil compaction occurs, the worse the natural recovery is.

2.1.2 Freeze and thaw

The process
The annual freeze-thaw cycle (FT cycle) is one of the processes that affect soil structure. The freeze-thaw process has a strong influence on water transport and water content in the soil. With the decrease of soil temperature below 0 °C, water will pass from the liquid phase to the solid phase. As a result, the volume of water increases by about 9% (Zhao et al. 2004). The ice crystals in the pores press the soil particles closer together and thus disrupt the existing soil structure. In addition, the freezing of the water causes water to flow to the ice crystals and dehydration of the soil takes place (Sun et al., 2021) (Figure 2-6). This dehydration causes in particular clay soils to decrease in volume. So, the freezing process can cause both volume increase and volume decrease.

Dagesse (2010), based in part on research by Hamilton (1966), determined that the initial water content at the start of the freezing process strongly determines the magnitude and direction of the volume change. The volume change due to freezing has three distinct phases depending on the water content at the time of freezing (Figure 2-7).

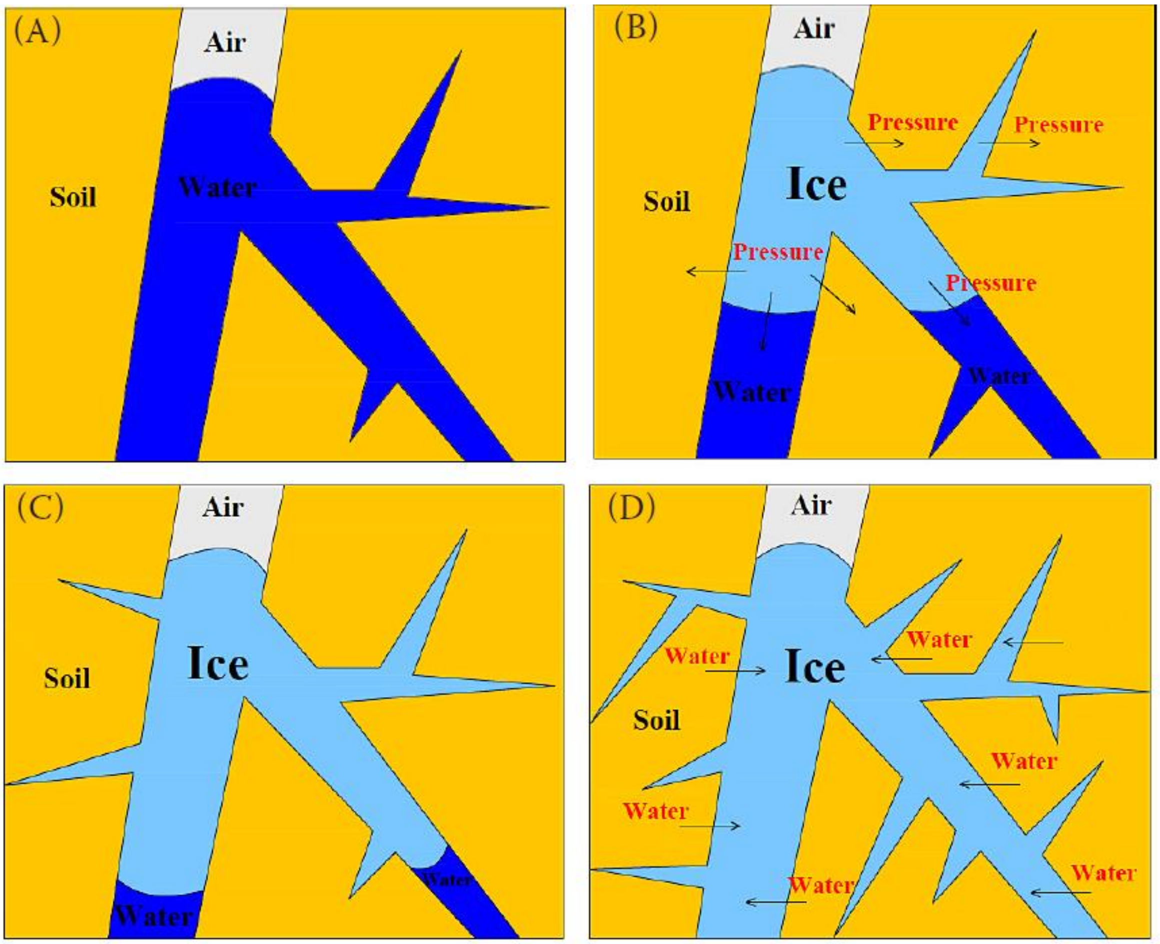

Figure 2-6 *Soil moisture phase change and migration during freezing-thawing process (Sun et al. 2021 after Gao et. 2016).*

1. Under dry conditions (about 20 - 40% water content), little water is available to freeze or flow to the growing ice crystals, and the volume change is very limited.
2. When the initial water content increases (about 40 -60%), a volume reduction is seen under freezing conditions. In this case, the air-filled pores are large enough to accommodate the volumetric change associated with the phase transition. At the same time, a flow to the ice crystals takes place, causing the soil to dry out and shrink.
3. From an initial water content of about 65%, the expansion process takes over and the volume reduction will change to a volume increase.

The research of Dagesse (2010) shows that independent of the clay content, at a water content of around 65% the greatest volume reduction occurs (Figure 2-7). The extent of this volume reduction depends on the clay content and lies between 1 and 10% (clay content between 10 and 75%). The increase in volume due to expansion is less dependent on the clay content and lies between 2 and 4%. Soil texture and initial water content are thus the important factors in the volume change due to the freezing process.

Whether that volume change during freezing will provide a permanent improvement in soil texture after thawing may depend on which freezing process is dominant. Kay et al (1985) note that the freezing process caused by the expansion of ice crystals creates unstable pores that disappear after the water melts and drains. This may contrast with changes in structure caused by tillage or shrinkage (see also the section on swelling and shrinkage).

Experiments on freezing and thawing

In recent years, several studies have been conducted on the effect of freezing and thawing of soils. These studies provide very different results with sometimes positive and sometimes even negative effects on soil structure. Both Jabro (2014) and Sun et al. (2021) listed various studies from the past decades and concluded that the results are highly inconsistent. Schjonning et al. (2017), based on a review of various studies, conclude that even annual freezing to a great depth (> 1.0 m-mv) is unable to permanently resolve subsurface compaction. They also indicate that the potentially positive effect of freezing disappears again during thawing.

For this state-of-the-art study, the various studies (dozens) have not been extensively reviewed. However, a quick review does show that the various studies differ greatly with respect to soil type, initial moisture content, depth to which frost occurs, and the number of FT cycles during a season. In addition, the studies use various parameters to demonstrate the effect of freezing and thawing; they look at primary soil parameters (pore volume) and/or penetration resistances and/or permeabilities or water retention. Finally, some studies focus on shallow soil compaction (up to 30 cm) mostly in combination with no-tillage practice, while others focus more on the deep subsurface (30- 90 cm -mv). All these factors make comparing the various studies and drawing conclusions about effectiveness complex.

Positive effects of freezing and thawing have been demonstrated in several studies. For example, Jabro et al. (2014) concluded for a clay soil in Montana that the freeze-thaw cycle reduces soil compaction by 60% to a depth of 30 cm. However, some of this improvement is caused by the swelling and shrinking of the clay. Henry (2007) and Unger (1991) also observe a reduction in soil penetration resistance and bulk density during winter due to frequent freeze-thaw cycles. Studies by Edwards (2013); Fouli et al. (2013); Sahin et al. (2008) and Siarajan et al. (2018) have shown that repeated freeze-thaw cycles loosen soil structure, reduce soil compaction and improve soil physical and hydraulic properties. All of these studies have looked at the topsoil (< 30 cm -mv. Both Voorhees (1983) and Alakukku (1996) show that despite repeated FT cycles, soil compaction below the plough layer (subsoil >30 cm) did not disappear.

Optimizing the effectiveness of freezing and thawing

Various studies show that freezing and thawing can have a positive effect on the elimination of subsoil compaction. However, the results indicate that for the deeper subsoil (> 30 cm) the effect can be limited and also that part of the possible positive effect disappears when the soil thaws again.

Freezing and thawing are not possible for all areas. Firstly, frost must penetrate the ground to a great depth for several years. This means that for Europe only the Scandinavian countries experience these conditions (see also Chapter 4.2). Tillage and the presence of cover crops influence the depth to which frost can penetrate. Furthermore, clay soils improve more due to freezing and thawing than sandy soils. This is caused by the fact that clay soils (> 20% clay content, Dagesse, 2010) can dry out strongly as a result of freezing and thus shrink.

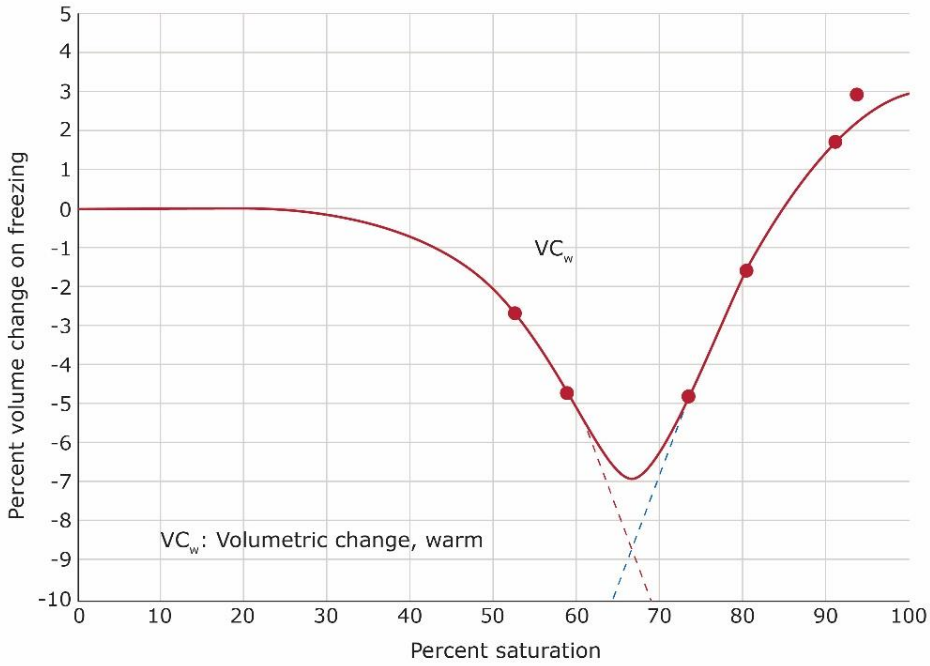

Figure 2-7 *Combined volumetric change versus percent saturation curve for Hamilton's - 6.7 °C data (After Dagesse, 2010).*

2.2 Mechanical recovery

Deep tillage is used to break through naturally disturbed layers, improve soil structure, improve bearing capacity or lift mechanically compacted layers. The techniques used for this purpose are subsoiling (loosening), deep ploughing (turning) and deep mixing. Schneider et al (2017) give an overview of the various techniques and visualize the effect (Figure 2-8,
Figure 2-9). Subsoiling aims at loosening the soil structure and decreasing the bulk density of the subsoil without turning or mixing soil horizons. In contrast, deep ploughing turns soil horizons and results in complete or semi-complete inversion of the soil profile, with subsoil horizons ending up at the soil surface and topsoil horizons buried in the deep soil. Finally, there are deep tillage options that mix subsoil and topsoil.

Spoor et al. (2003) state that the lifting of a compacted layer should take place as much as possible through biological and physical processes, possibly supplemented by limited deep tillage. Deep tillage is often accompanied by considerable discharging, rearrangement of the soil and loss of bearing capacity. Such disturbance is highly inappropriate for protecting the subsurface from future loading and preventing its rapid recompaction. The main purpose of deep tillage for recovery of subsoil compaction should be to create cracks or fissures in the compacted zone. This will allow rooting and drainage to be restored while minimizing disturbance to the remaining part of the soil profile. Spoor et al. (2003) call this "fissuring without loosening." This means that for the recovery of subsoil compaction, subsoiling (loosening) can be preferred over deep ploughing and deep mixing. This conclusion is confirmed by practical tests (sandy loam) with various deep tillage techniques to remove compaction in the Netherlands in the 1990s; here deep ploughing and deep mixing resulted in quick re-compaction. (Kooistra and Boerma, 1997).

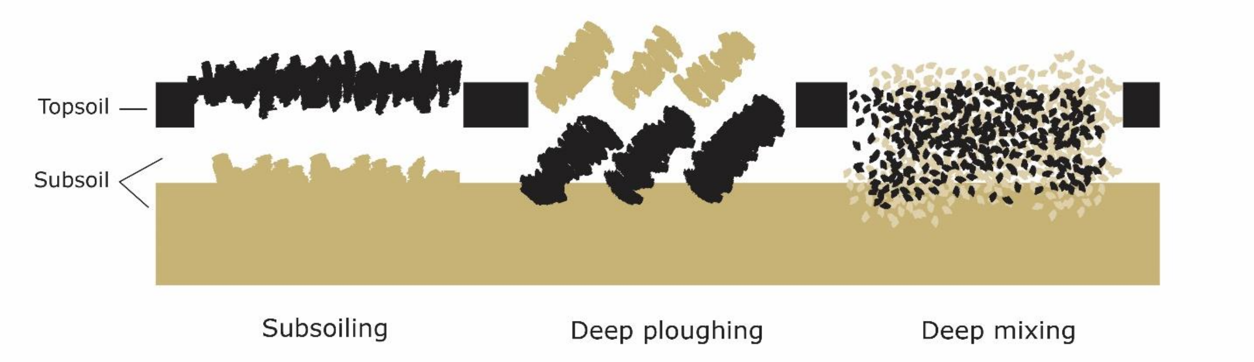

Figure 2-8 *Schematic drawing of deep tillage methodes (After Schneider et al., 2017).*

2.2.1 Subsoiling

The process

Koolen (1985) states that loosening through subsoiling can be achieved through brittle disturbance or tensile disturbance. In the case of brittle disturbance, the soil is fractured and the resulting aggregates slide upwards allowing the soil mass to expand and hence be loosened. The aggregates are rearranged with reference to each other as they are lifted and fall back down (Figure 2-11). With tensile disturbance, the entire mass of soil is lifted upwards, this mass is cracked as it bends over the top of the wing before falling back down (Figure 2-11). Generally, the degree of loosening is greater if the soil experiences brittle rather than tensile disturbance (Weill, 2015). Spoor et al. (2003) state that subsoiling should be particularly focused on creating a tensile soil failure within the compacted area, where cracks are generated, leaving the soil mass between the fissures largely intact, unbroken and strong (Figure 2-10).

Figure 2-9 *Pictures of different deep tillage methodes, subsoiling, deep mixing and deep plouging (Van Balen en van den Akker, 2020).*

Experience with subsoiling

The experience with subsoiling and its effects on crop yield have been described in detail in two meta-studies by Schneider et al (2017) and Yang et al (2022a). A general picture emerges from Schneider et al (2017) that subsoiling can restore subsoil compaction but that there is a high risk of re-compaction. This danger occurs particularly if subsoiling is performed under too wet conditions (Schulte-Karring et al., 1993). On the other hand, subsoiling may also be ineffective when conditions are too dry, especially for heavy soils. Furthermore, they observed that re-compaction occurs particularly in soils with high silt content (> 70%) and low clay content (< 20%) and is less observed in clay soils (> 20%). In clay soils, re-compaction is highly dependent on the type of clay with kaolinite being the most sensitive. The meta-analysis also shows that growing crops with extensive root biomass for several years after subsoiling can have a positive effect and stabilize the mechanically loosened soil structure in the long-term. This positive effect is also described in several other studies (Kooistra and Boersma, 1994, Wanink et al., 1990, Olesen & Munkholm, 2007). Also, Weill (2005) indicates that subsoiling can help alleviate compaction, but it also can be ineffective and even detrimental to the soil if the operation is not well planned or if it is carried out under poor soil conditions.

Even when done in good conditions, the volume of loosened soil can be insufficient and, in some cases, the soil can be compacted at depth instead of being loosened.

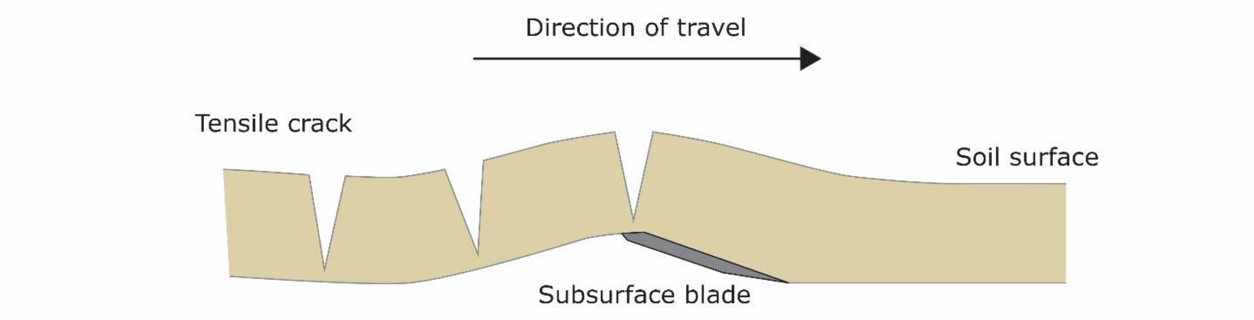

Figure 2-10 *Tensile soil failure with subsoiling (After Spoor et al., 2003).*

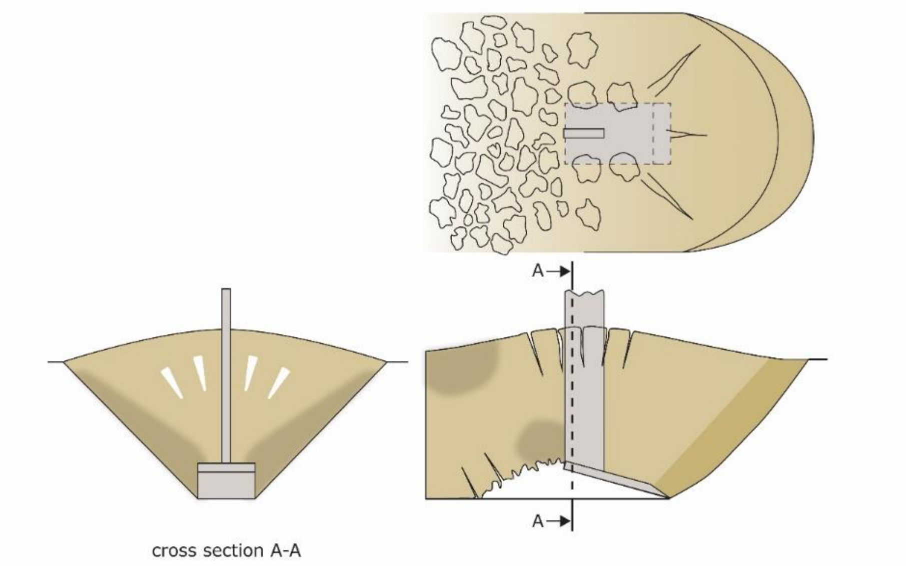

Figure 2-11 *Schematic drawing of the subsoil process. Dark shade: brittle disturbance, stripes: light shade: cracks/fissures, top view and side view (After Koolen, 1985).*

Successful subsoiling depends not only on soil conditions. Other factors such as tractor power, balancing, and subsoiler adjustments play an essential role in obtaining good results (Weill, 2015). Also, in agreement with Spoor (2006), Weill (2015) emphasized the danger of compaction during subsoiling due to improper implement selection and excessive tillage depth.

Subsoiling under specific conditions
Much research has been done on the use of subsoiling to improve soil structure. Only a limited amount of research has been focused on the recovery of subsoil compaction. What is important for recovery is that subsoiling techniques are chosen in which the soil is cracked but in which there is very limited loosening. These preserves bearing capacity and reduces the likelihood of recompaction.

The moisture conditions and texture of the soil are strong determinants of whether or not subsoiling restores subsoil compaction successfully in the long term or if recovery must be repeated regularly. In general, subsoiling on relatively light soils (clay < 20%) has a high chance of recompaction in the short term (3-4 years). This recompaction is, however, strongly dependent on the mechanical load after subsoiling. In general, it would be advisable not to till the soil and to drive with limited loads for a few seasons after subsoiling (Schulte-Karring et al., 1993). If this is not feasible, then it is important to sow a cover crop to preserve the mechanically loosened soil structure.

2.2.2 Bore-hole method

The process

Drilling of smaller or bigger holes, through compacted soil layers, can help to create pores in which plant roots can grow and water can infiltrate. The advantage of this system is the minimizing of soil disturbance and so preservation of soil bearing capacity. The lower the soil bearing capacity is, the higher the risk of soil (re)compaction. The bore-hole method is an alternative to the most common tillage operation to eliminate topsoil compaction and subsoil compaction with the use of a chisel plough or other equipment to break compacted soil layers.

Experience with bore-holes

In Switzerland, experiments have been conducted in which holes of 1.25 mm (diameter) were pierced in compacted soil, up to a depth of 20-30 cm below ground level (Colombi et al., 2017). Plant roots used these artificial macro pores because of reduced resistance to root penetration and an improvement in air permeability.

Experiments with pierced holes of Ø 1 cm (5 holes in a circle around a plant) and hand-drilled bore holes of different diameters (Ø 6-10 cm) and depths (30-60 cm) were performed by Yang in 2017 and 2018 on a compacted sandy soil in the Netherlands and a sandy loam soil in China (Yang, 2022b) see Table 2-1. The experiment in the Netherlands contained three bore-hole treatments, two manure treatments and two crops (silage maize and sorghum). Plots were 1 m^2 with 9 plants/m^2 and each drilled hole of Ø 6 or Ø 9 cm was sown with a crop on top of the surface after closing of the bore-holes. The application of manure consisted of a mixture of soil and organic manure that was applied in the bore holes or applied on the surface and slightly incorporated. The experiment with small pierced holes was performed in 2017 in the Netherlands only. In China, the experiment was conducted in 2018 on two plots (Yang, 2022b). Plant density was 9 plants/m^2 for maize with a plot size of 1,34 x 1,34 m and there was a bore-hole of Ø 7 cm or Ø 10 cm for each plant in two depths (30 or 60 cm). This experiment had ten treatments consisting of five bore-hole treatments and two manure treatments. The yield was not every year significantly higher on the sandy soil, whereas the wider holes on the sandy loam soil resulted in the highest yield. The application of manure did not result in a higher grain yield (winter wheat, maize) or total biomass in both locations. Although roots grow preferably in bore-holes, no significant difference was found in root weight on the sandy soil. In one of the experiments in China, the total root weight was higher in bore holes in the top layer (0-20 cm). Soil compaction was concentrated in the top layer.

Table 2-1 *Location, year, crop bore diameter and depth of bore-holes in the experiment of Yang, 2022b.*

Site	Year	Crop	Bore diameter	Depth in cm
Odiliapeel	2017	Maize & Sorghum	1 cm	60 cm
			6 cm	60 cm
	2018	Maize & Sorghum	6 cm	60 cm
			9 cm	60 cm
Luancheng North & Luancheng South	2018	Maize	7 cm	30 cm
			7 cm	60 cm
			10 cm	30 cm
			10 cm	60 cm

A combination of the bore-hole technique, amendment of organic matter and deep rooting crops is currently performed on sandy soil and sandy loam soil in the Netherlands within the framework of the public-private partnership *Climate Adaptation Open Cultivation project* (results expected in 2023, Van Balen, 2023). A tractor-mounted machine is built with drills of 2,5 cm diameter, at a distance of 25 cm and drills of Ø 10 cm at a distance of 75 cm. This machine can make bore-holes up to a depth of 60 cm below ground level (Figure 2.12). The advantage of drilling holes is that soil is removed from the compacted layer so that a certain rebound occurs in the compacted layer and the resistance of the soil next to the hole to penetration by roots may be reduced. Instead of 2,5 cm drills, rods of 2,5 cm can be used to pierce a compacted soil layer.

Disadvantages of this method are the huge force that is needed in a compacted soil and the density is slightly increased locally. The big holes (10 cm) are filled in the bottom half with coarse sand or compost depending on the effect of soil compaction on soil conditions and plant growth (Figure 2.13). Coarse sand will have a better drainage effect and is very stable in the soil. This is applied on clay soil. Compost or other organic material will stimulate root growth but is expected to 'dissolve' in the soil within time and is applied on sandy soil. The combination of deep loosening of the soil and placement of nutrients can enhance root growth (Schulte-Karring et al., 1993). Compost is not only a source of organic matter but also of nutrients that can stimulate root and plant growth. With the amendment of 2.5 liter of compost per bore-hole will 36 ton compost be added per hectare. From this compost about 18 kg N, 48 kg P_2O_5 and 173 kg K_2O per hectare will be plant-available in the first year after application when the compost is applied in the top layer were most of the roots grow. The nutrient effect on growth is probably low because of compost application in the subsoil.

Figure 2.12 *Tractor mounted machine with 10 cm drills (van Balen, 2023).*

Figure 2.13 *Freshly made bore-holes Ø 10 cm 75 cm apart filled with compost (van Balen, 2023).*

Optimizing the effectiveness of drilling holes

The experiments by Yang show that plant roots prefer the wider bore-holes for rooting to deeper layers when plants are sown in the top layer of each bore-hole. This resulted in a higher yield depending on soil type and year. There was no indication that roots make use of the smaller bore-holes (Yang, 2022b). The effect of the loose soil in bore-holes can be optimized when plants grow above these bore-holes. This is feasible with modern accurate gps techniques but depends on the distance between the crops that are grown. The row distance of arable crops varies between 12,5 and 75 cm in the Netherlands. A row distance of 25 cm would be most suitable for most of the cash crops. Although the expected machine power that is needed is much lower when bore-holes are drilled compared to the use of a tine or chisel plough for decompaction of the subsoil, this technique is time-consuming. The prototype machine in (Figure 2.12) is operated by one person but every drilling operation of 1,5 m^2 takes 1 minute (1,78 holes/m^2). Further analysis of this method is needed to determine the right number of holes per m^2, diameter, depth and material added in the holes. An autonomous vehicle and tool can help to make this technique economically feasible. But even then, the drilling is time-consuming and should only be used on severely compacted soil.

2.3 Biomechanical recovery (biosubsoiling)

The process

Elkins (1995) pointed out that plant roots can be used to change soil physical conditions as they can exert forces on soil. Legumes and perennial grasses can improve soil structure in the plough layer and some plant roots can grow through compacted soil layers (biosubsoiling). The macropores (biopores) that are left after the decay of plant roots improve water movement and diffusion of gases. And these biopores can be used by succeeding crops. To accomplish root growth in compacted soil, some physical restraints must be overcome. There is a mechanical impedance caused by lack of space to store displaced soil particles by root growing. A compacted soil also has a negative effect on water infiltration, water retention, gas permeability and exchange, nutrient cycle and habitat for soil organisms, resulting in suppression of root growth (Bakema et al., 2023). Lipiec et al. (2012) found, in an experiment with undisturbed soil samples, a reduction of 50% of the root length for barley and 79% for triticale in compacted soil compared to non-compacted soil.

Root systems of different plant species react differently to soil compaction. In general, a penetration resistance force of 0,8-2 MPa is enough to reduce root length growing. A penetration resistance force of 5 MPa actually stops root growth. Another physical quantity to express the effect of soil compaction on root growth is dry bulk density. A dry bulk density of ~1.47-1.58 g cm^{-3} in clay soils and 1.85 g cm^{-3} in sandy soils is obstructing root growth (Bakema et al, 2023).

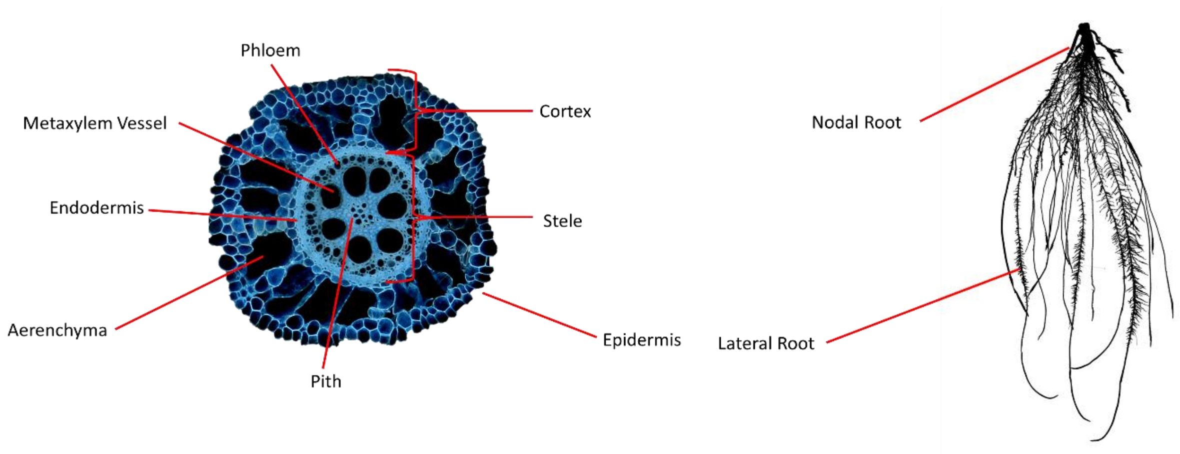

Figure 2-14 *clarification of some specific root physiological terms in (a) transverse section and (b) length (Bakema et al, 2023).*

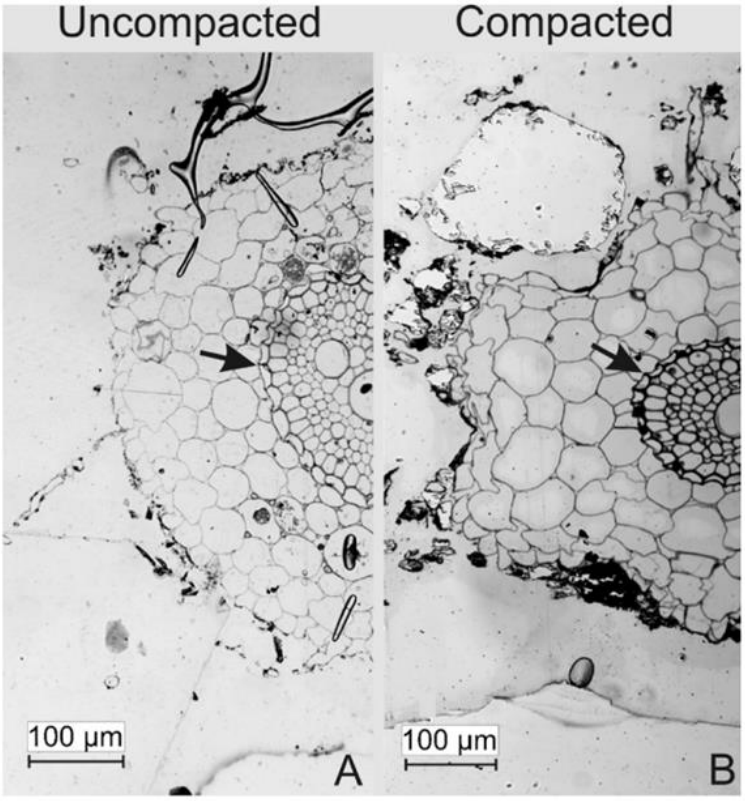

Figure 2-15 *Anatomy of wheat root (arrow, border between vasculair cylinder and cortex) (Lipiec et al, 2012).*

Plants have the ability to adapt the root system to the growing conditions. An overview of the different strategies plant have developed to soil conditions is displayed in Figure 5.1.

The area of the cortex and/or vascular cylinder is decreased or increased in reaction on soil compaction (Figure 2-, 2-14 and 2-15). The diameter of the vascular cylinder and thickness of the cortex of roots grown in compacted soil becomes bigger. These different reactions of plant roots indicate that the variability in growing conditions is bigger in compacted soil. Plant roots can adapt to situations in which soil penetration resistance increases. Exudates from plant roots act as a lubricant and sloughing (shedding of superficial plant cells) reduce friction on the root tip (Colombi and Keller, 2019). The risk of bending or breaking of roots is limited by increasing root diameter when penetration resistance increases. And the ability to grow roots at sharp angles makes it possible to grow in soil conditions with a high penetration resistance. Besides adaptation of root strength, plants can also change the internal oxygen transport and make a connection between the lower and upper root systems (Colombi and Keller 2019). The ability to grow roots in compacted soil is determined by the increase in thickness of cell walls and area but also in a number of cortical cells and diameter of the stem.

Experience with biosubsoiling
Deep-rooted crops can break through a compacted subsoil and have the added advantage that they are less susceptible to dehydration. Various crops have been tested on these properties in the past, such as cover crops with deep tap roots (radish and lucerne), rapeseed, fibre hemp and rye (CLM, 2016). In addition, sorghum has been studied and can be used as a supplement or interchange crop with maize. German research comparing maize with various types of sorghum on a highly compacted sandy loam shows positive results. Besides a much deeper rooting than maize, sorghum leaves much more root remains (50-80% at a depth between 20 and 100 cm -mv) in the soil (Schittenheim and Schroetter, 2014). In the Netherlands, a comparison was made between maize and various types of sorghum on experimental fields in Lievelde (loamy fine sand), where in addition to yield, rooting was also examined. Compared to maize, 40% more roots were present at a depth of 25-40 cm depth. Furthermore, the rooting of sorghum was found at greater depth (Deru et al., 2018).

In general, research on sorghum is mainly aimed at selecting for yield and drought resistance; specific selection for breaking through compacted layers has been carried out to a limited extent. A field trial in the Netherlands shows that, although sorghum has a finer and more intensive root system than maize and has a higher root mass in deeper layers (measured up to 50 cm), recovery of soil compaction wasn't observed (Van den Akker et al., 2021). The variation in rooting was variety-dependent for sorghum (especially biomass types with low nutritional value have a deeper rooting). In addition, sorghum seems to be sensitive to low soil temperature or too dry topsoil after sowing and during the germination phase, which caused the plant to not develop optimally, especially in the extremely dry summers of 2018 and 2019 (Heinen et al. 2021).

Maize varieties appear to react differently to soil compaction in field experiments. One variety performed better in compacted soil and this variety was more drought resistant than the other (Xiong et al, 2020). Less root growth and delayed development of side roots have consequences for the root abundance in the topsoil. Plants will increase the number of roots in the top layer with increased water uptake and root respiration, resulting in a higher penetration resistance and amount of oxygen in the soil. (Colombi and Keller 2019).

The succession of crops can help to improve rooting capability. Tap roots are able to penetrate deeper soil layers and create biopores (with lower penetration resistance) in which roots of succeeding crops can grow (Chen and Weil, 2010) and Figure 2-16 (Zhang and Peng, 2021). The roots of a crop like forage radish (*Raphanus raphanistrum* subsp *sativus*) are more capable of penetrating compacted layers than the roots of rye (*Secale cereale*). Roots of forage radish have a larger diameter than roots of rye. This confirms earlier findings that roots with a large diameter can easier penetrate compacted soil than roots with smaller diameter.

It's not only the diameter of the roots but also the design of the root system. Both forage radish and rapeseed (*Brassica napus* subsp *napus*) have a tap root but tillage radish has one tap root with thick branches and rapeseed has several tap roots and side roots that are thin-shaped (Chen and Weil, 2010).

Dicotyledonous plants have in general a better ability to penetrate compacted soil than monocotyledonous crops. The difference is probably related to the ability of dicotyledonous crops to increase root diameter when there is an increase in root pressure (Cresswell and Kirkegaard, 1995).

Colombi et al (2018) found no difference in the total biomass of roots up to 62,5 cm depth in compacted and non-compacted tilled soil compared to no-tilled soil. But in compacted the soil the roots were concentrated in the top layer. Increased penetration resistance resulted in a lower number of lateral and axial roots and an increase in root diameter. Increased bulk density and penetration resistance will not always result in lower plant production, but plants are less able to exploit the soil for water and nutrients with a shallow root system.

Although roots of cover crops can penetrate compacted layers, no significant effect was found on soil bulk density or penetration resistance in the year following the cover crop. An explanation is the use of biopores created by the roots of the cover crop by the following crop (Chen and Weil, 2010). Although the yield was higher of wheat grown after rapeseed and roots of rapeseed were found at 1,70 m depth, no changes in subsoil structure were found (Cresswell and Kirkegaard, 1995). A two-year experiment with different cover crops on compacted soil did not affect dry bulk density. Soil water content was decreased by cover crops which had probably an effect on penetration resistance, which was significantly higher when cover crops were grown. A significant increase in maize root characteristics (root mass density and root length density) and yield was found in compacted soil by the use of cover crops. This could be the effect of the benefit of root channels of previous cover crops for the following main crop (Zhang et al, 2022).

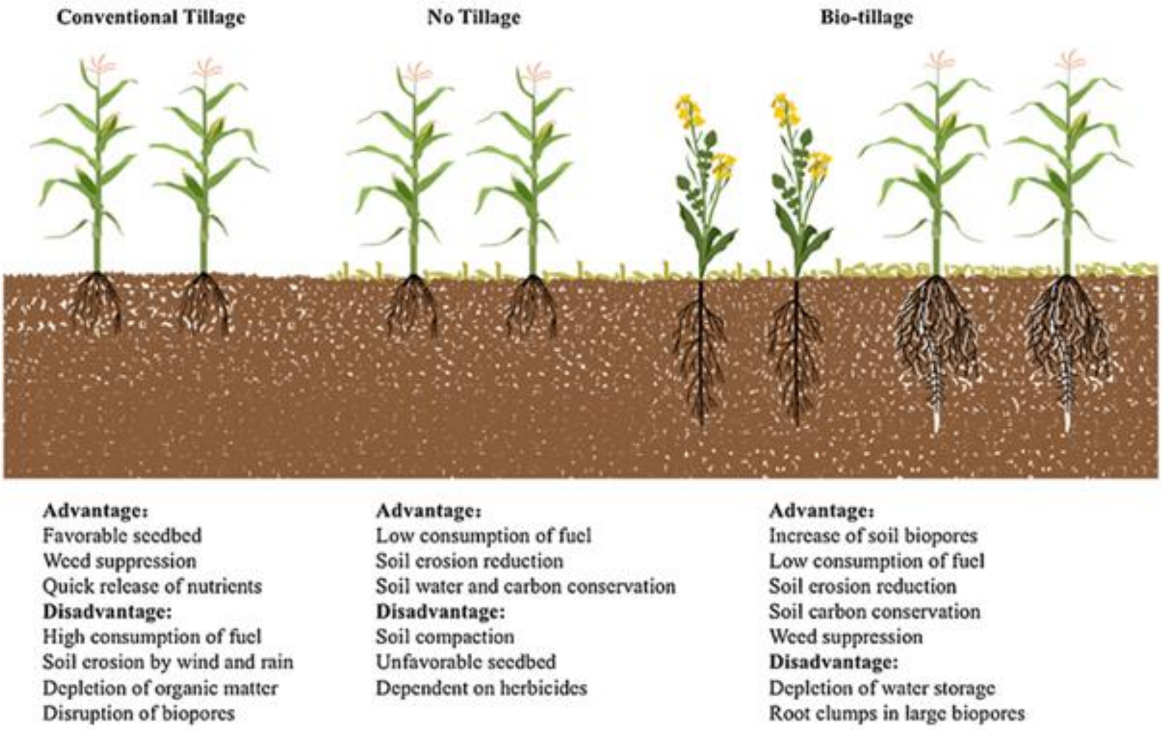

Figure 2-16 *Comparison of conventional tillage, no tillage and biosubsoiling (Zhang and Peng, 2021).*

Optimizing the effectiveness of biosubsoiling
Soil water content is of great influence on penetration resistance and oxygen concentration in the soil. A dry soil will increase penetration resistance and a very wet soil increases the risk of low oxygen concentrations in the soil. Plant species can adapt to changes in soil conditions. The roots of a pea plant for example are better at recovering from low oxygen concentrations or high penetration resistance than the roots of wheat. (Bakema et al, 2023). Dry soils can have the same physical properties (penetration resistance) as compacted soil. Annual crops that are adapted to dry conditions probably have the ability to grow in compacted soil also. An example is sorghum which has a main root (seminal root) followed by nodal roots in a later growing stage. This root system is different from other monocotyledonous crops like maize, which has several seminal roots followed by nodal roots.

Whether biosubsoiling can be effective to alleviate soil compaction depends on the crops used in the crop rotation and on the growing conditions. Crops with tap roots are preferred over crops with fibrous roots. Well-drained soils have less risk in very wet soil conditions and low oxygen concentrations in the soil. The selection of plant species, to be used in biosubsoiling, can be based also on their ability to grow in dry soil conditions because of comparable physical soil conditions of dry soil to compacted soil.

The length of the growing period of a crop (perennial, annual) is of influence on the effect of plant roots on soil structure. Besides the growing period, morphological and physiological characteristics of the root system, like root tip pressure and resistance to root buckling, are important for the ability of roots to penetrate compacted soil layers (Cresswell and Kirkegaard, 1995). The length of the growing period of a crop is probably more important to resolve soil compaction than the ability of roots to penetrate compacted layers. Plants can face several growing conditions (due to different soil water contents) during the growing period, which enable the plant to extend the root system. This makes perennial crops capable to penetrate the soil up to 2–3-meter depth (Cresswell and Kirkegaard, 1995).

The longer the growing period of a crop the more opportunities roots have to penetrate in deeper soil layers. Different soil moisture conditions will cause swelling and shrinking which results in cracks (see paragraph 2.1.1). Plant roots can penetrate and colonize these cracks when they are open. Plant roots that are already present in the topsoil have more change to grow in subsoil cracks before these cracks close again.

Plant roots can help to penetrate compacted soil layers and in this way improve soil structure with biopores but there is also a side effect of rhizodeposits and the input of organic carbon from decomposing roots. This can increase the abundance and activity of earthworms and micro-organisms, and consequently the number of biopores and stable soil aggregates (Ning et al, 2022).

Anecic earthworms make vertical burrows and help to reduce the negative effects of intense rainfall conditions by increasing the infiltration capacity of the soil. Earthworm burrows are semi-permanent and play a role in water drainage and gas exchange (Andriuzzi et al, 2015). Hydraulic conductivity increased in eight out of nine experiments with *Lumbricus terrestris* (Joschko et al, 1989). Earthworm burrows act as biopores and can be used by plant roots even when earthworms are not present anymore (Figure 2.17) The anecic earthworm *Lumbricus terrestris* is capable of penetrating a plough pan. These earthworms have the capacity to make burrows in compacted soil (40% pore volume). The more compacted the soil, the more casts were found on the surface as earthworms in loose soil push soil particles aside which is not possible in compacted soil (Joschko et al, 1989). The uptake and excretion of soil particles by earthworms also affect bulk density. An equilibrium in bulk density is reached after earthworm activity and these soil conditions are favourable for stability in soil structure and root development. In the cited experiments, the bulk density of loose soil was increased but the bulk density of compacted soil lowered from 1300 to 1200 kg/m3. An amount of 20 grams of earthworms per m^2 can entirely ingest and excrete a topsoil of 20 cm in 50 years (Barré et al, 2009).

Earthworms can be of help to plant roots to penetrate deeper soil layers. But the living conditions for roots must correspond to the conditions required for earthworms (availability of food and soil moisture, reduced tillage).

Implementation of biosubsoiling in existing farming systems can be difficult. Not all farming systems are suitable for biosubsoiling. Changes in tillage and crop rotation can have a large impact on economic return.

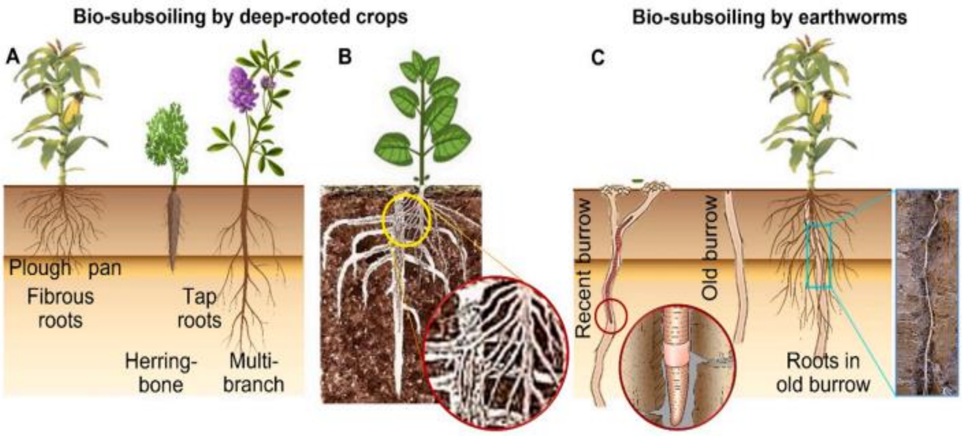

Figure 2-17 *Bio-subsoiling by deep rooted crops (left and middle) and earthworms (right). A: deep-rooted crops such as carrot, alfalfa, chicory etc., can be used as bio-subsoilers. Tap rooted species penetrate compacted layers better than fibrous-rooted species. Taproot-multibranch crops enlarge the pore system with more and larger biopores than taproot-herringbone roots. B: Subsequent crops can use the remaining biopores (white parts in soil) created by preceding deep-rooted crops. C: Anecic earthworms are vertical burrowers, which can create vertical biopores up to 2.4 m deep. Old and new burrows can be used by growing crops to uptake water and nutrients below the plough pan. The loupes (B and C) show the new roots growing in the depth through the old biopores (B: root biopore; C: earthworm biopore). (Ning et al, 2022).*

3 Recent experiments with recovery techniques

3.1 Overview of experiments

This section evaluates how the above-mentioned recovery methods are occurring in current and past field compaction experiments across Europe. To ascertain this, a questionnaire was circulated among researchers working in the field of soil compaction and recovery.

3.2 Methodology

The questionnaire (Annex 1) aimed at evaluating the effectiveness of natural, biological and mechanical techniques for recovering the functionality of compacted subsoil. There were ten respondents from seven European countries (Denmark, Switzerland, Netherlands, Spain, Lithuania, Turkey and Germany), providing data from 14 field sites. The soil types at these sites ranged from sandy soil to heavy clay soil, with the majority being loams. The field sites were originally compacted between 1993 and 2019, and most of the compaction studies were conducted in the 20-70 cm layer below the soil surface. The recovery period ranged from 1 year to 12 years after compaction. Details about the specific field experiments are provided in Table 3-1.

In order to identify the effectiveness of the recovery mechanisms from the experiments, the measurements that were analysed must have been conducted both right after the compaction event and after the recovery period.

Based on the experiments described in Table 3-1, the effectiveness, economic aspects and perceived stakeholder acceptability of the recovery approaches are discussed. The different recovery methods were evaluated according to the following criteria: (i) effectiveness in the short (< 2 years) and long term (> 2 years), (ii) possible negative side effects, (iii) costs and benefits, (iv) technology readiness, (v) acceptance by farmers and co-workers (socio-economic aspects). It is important to note that due to the small number of experiments (14), any conclusions drawn here are only preliminary and should be interpreted with caution.

Table 3-1 Compaction or tillage experiments included in the report.

Country	Institution	Project/Experimental Site	Soil texture or type	Climatic zone	Year of initial compaction	Soil depth (cm)	Wheel load (Mg)	Recovery techniques[1]	References
Denmark	Aarhus University	3 sites: Årslev, Tåstrup, Flakkebjerg	Sandy loam	Atlantic	2010	20-60	5-10	N, B, N+B	Schjønning et al. (2017); Obour et a. (2017); Pulido-Moncada (2021; 2022)
Switzerland	Agroscope	ROCSUB	Loam	Continental	2019	0-70	N/A	M, B, N+B,	Johannes et al, 2022
Lithuania	LAMMC	DOTN-1 (Tillage, cover crop experiment)	Loam	Boreal	2003	0-20	1-5	N, B, N+B	*Not available*
Spain	CSIC	Southwest Madrid	Calcic Luvisol	Mediterranean	2002	0-30	N/A	M	López-Fando & Pardo (2009)
Germany	Göttingen	Reinshof	Silt loam	Continental	1995	40	5-10	N	Mähner (1999)
Switzerland	Agroscope	Soil Structure Observatory	Loam (Cambisol)	Continental	2014	50	5-10	N, N+B	Keller et al. (2017; 2021)
Netherlands	Louis Bolk Institute	3 sites	Sand, Light Clay, Heavy clay	Atlantic	?	?	?	N, M, N+M, N+M+B	De Boer et al. (2018); De Boer et al. (2020);
Lithuania	LAMMC	Long-term tillage expt	Sandy clay loam (Retisol)	Boreal	2010	0-45	?	N+M, N+B	*Not available*
Netherlands	WUR Field Crops	Lelystad+Vredepeel	Sandy loam, Sand	Atlantic	2019	60 & 40	?	M+B & N+M+B	Van Balen et al. (2021);
Turkey	TAGEM, GAP Agric Inst.	Koruklu Exp Res Station	?	Anatolian	2011	0-15/0-30	?	B, N+M	Çıkman et al. (2017; 2020)

[1]N = natural (freeze-thaw, wet-dry, and shrink-swell cycles); B = biological (roots and soil organisms), M = mechanical (subsoiling).

3.3 Results

3.3.1 Measured variables

The variables most frequently measured were crop yield, bulk density and penetration resistance. Other functional soil properties related to water and gas flow received less attention (Figure 3-1). All three mechanisms were in play at the field sites, but the natural (freeze-thaw, wet-dry, shrink-swell) and biological (plant roots and macro organisms) were present in at least half of the field experiments (Table 3-1).

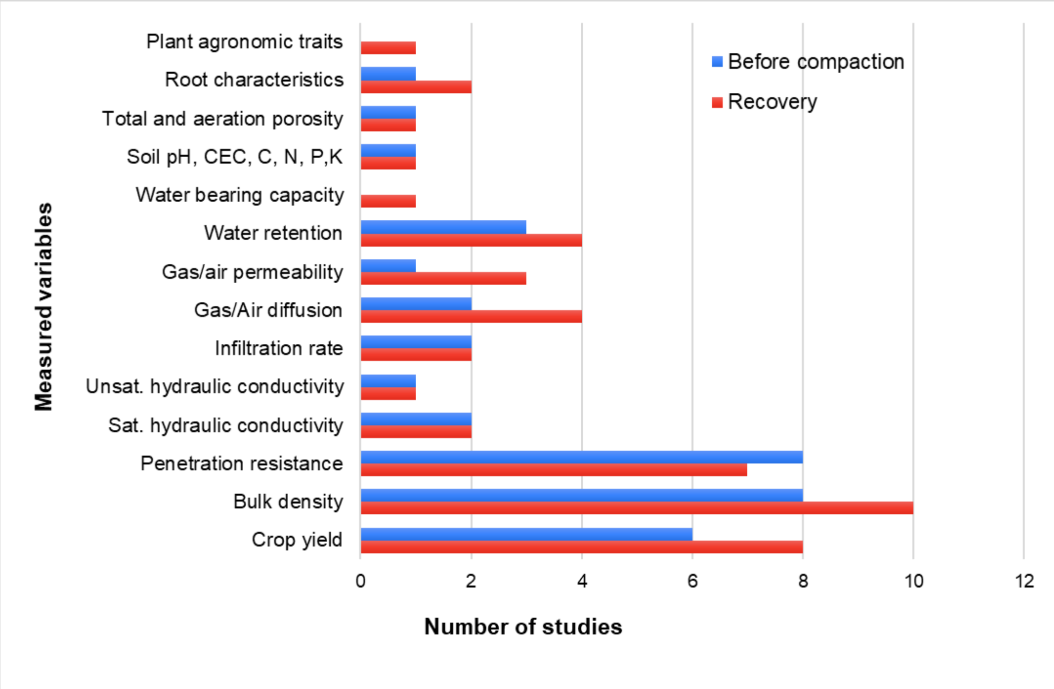

Figure 3-1 *Soil and plant variables measured before compaction and during the recovery phase.*

3.3.2 Effectiveness of recovery techniques

The effectiveness of the recovery technique was quantified based on the recovery of compacted soil with regard to a specific variable. For example, the yield immediately after compaction is compared to the yield after the recovery period. The *recovery effectiveness* for the variables considered is defined as restored yields, bulk densities or penetration resistance to the levels existing before the soils were compacted.

The short-term (<2 years) effectiveness of the recovery approaches was generally low or very low (0-30% recovery of the measured variable) (Figure 3-2). The medium (30-50%) recovery was attributed to natural processes in silt loam soil in Germany 12 years after compaction. In Lithuania, a combination of natural, mechanical and biological techniques on a sandy clay loam led to a high (50-70%) recovery of bulk density, aeration and porosity. It is therefore difficult to disentangle the role of the different techniques in this unusually high recovery rate.

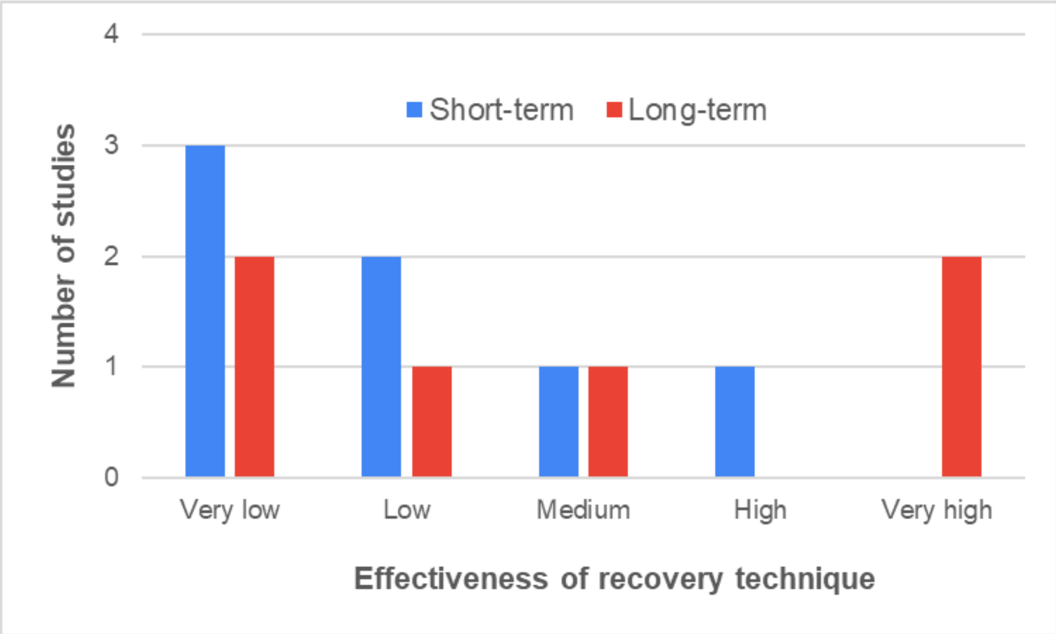

Figure 3-2 *Aggregated short (< 2 years, left) and long-term (> 2 years, right) effectiveness of recovery of measured variables to the levels existing before the soils were compacted.*

Recovery in the long-term (>2 years) was also low over the experiments analysed (Figure 3-2), except in two field sites (Germany, Reinshof and Turkey, Korukulu Experimental Station) that had very high recovery after compaction. The German field site exhibited a very high recovery from compaction of several variables (bulk density, penetration resistance, crop yield and other plant indicators) through natural processes. Considering the location of the field site, these natural processes are estimated to have involved freeze-thaw and wet-dry cycles. As explained in Chapter 2, natural recovery processes often take a long time to be evident in measured variables. The site had very high silt content, and the recovery investigations were carried out 22 years after the initial compaction event. Consequently, this very high recovery rate may be due to the long recovery time and high content of fine particles.

Potential negative effects

Despite the positive recovery rates reported in the previous section, there are potential negative side effects of the methods applied for recovery from soil compaction. These effects included: (a) cover crops as a biological recovery approach becoming a source of plant diseases, (b) a decline in soil pH in the short and long term, (c) a risk of re-compaction after mechanical subsoiling or loosening, and (c) decreased nutrient levels and crop yield after subsoiling.

Cost and benefit analyses of the recovery approach

According to 38% of respondents, the slow recovery process coupled with the expensive nature of mechanical approaches makes these unprofitable for use in farmers' fields. Others suggest that it will be profitable to use natural methods, including deep-rooted crops as an alleviation measure (25% of the respondents).

Technology readiness

The majority of respondents think that the readiness of the recovery approaches is at a TRL3 (experimental proof of concept) or TLR4 (technology validated in the laboratory) level. This is probably because few experiments can conclusively suggest an approach that works and is profitable for farmers.

Acceptance by farmers

The acceptance of an approach by farmers to alleviate compaction is crucial to its wide applicability. Considering the low TRL level attributed to the investigated methods, it was surprising that respondents perceived that stakeholders will accept the recovery approaches discussed herein.

Main conclusions

Based on the various experiments, the following conclusions can be drawn:

- The design and duration of the recovery techniques make it difficult to draw clear conclusions regarding the effectiveness of recovery of the soil from compaction. The reason is that almost all experiments used a combination of recovery techniques, and it was difficult to isolate the effect of one technique from another. Another reason is that the number of experiments studied is relatively small (n< 14).
- Complete recovery of soil properties from soil compaction was rarely observed in the experiments studied. In 11 out of 14 experiments, no more than 50% recovery of functionality of soil variables to levels prior to soil compaction was found.
- The researchers responding to the survey indicated that many of the recovery techniques they used are still in the experimental phase, so further monitoring is necessary.
- The measurements used to determine the effectiveness of recovery were limited to crop growth, penetration resistance and dry bulk density. In the experiments, virtually no measurements are made of air and water balance.

4 Effectiveness of technologies in different pedo-climatic conditions

4.1 Applicability for different soil types

Whether or not to apply a recovery technique depends heavily on the soil type. This study attempts to indicate whether a technique is applicable based on a rough classification by soil texture. The classification looked at the applicability and the degree of effectiveness of the technique and the risk of recompaction for different soil textures (Figure 4-1) (Table 4-1). The 12 standard USDA soil textural classes for mineral soils (indicated in Figure 4-1) were grouped into three broad classes: coarse-textured, medium-textured, and fine-textured soils. Peat soils are discussed separately.

Coarse-textured soils (clay < 20%, silt < 50%: sand, loamy sand, sandy loam)
Coarse-textured soils require little additional loading to become too dense to support crop growth or other soil functions. This is especially the case in sandy soils and/or loamy sands. This results in a dense, structureless 'concrete structure'. Furthermore, sandy soils have little cohesion. As a result, compaction causes not only densification but also deformation, which results in the loss of the large continuous biopores and old root courses. Natural recovery through swelling and shrinking and freezing is very limited in sandy soils. Since sandy soils are not cohesive the moisture level during subsoiling is not as important as it is for clay soils. This is why subsoiling can be carried out in the spring in some of these soils (Weill, 2005).

Medium-textured soils (clay < 20%, silt > 50%: – loam, silt loam, silt)
Silts and loams are the most susceptible soils to compaction because the pores between the more coarse grains can be filled with finer grains and lutum. Also, based on the meta-study by Schneider et al. (2017), it appears that re-compaction occurs particularly in soils with high silt content (> 70%) and low clay content (< 20%) and is less observed in clay soils (> 20%).

Fine-textured soils (clay > 20%, silt < 50%: – clay, silty clay, silty clay loam, clay loam, sandy clay, sandy clay loam)
Clay has a strong cohesion when it dries out, while it is more plastic under wet conditions. This makes well-drained clay soils many times stronger than sandy soils. As the clay content increases, the strength increases. The disadvantage of clay soils is that they remain wet longer under moist conditions, which limits the time in which these soils can be worked without compacting the subsoil. The advantage of clay soils is that they shrink considerably when they dry out and swell when they are moistened. This makes it possible for a compacted clay layer to partially regain its original structure. Subsoiling in clay soils must always be done when the soil is in a dry condition. Spring is never a good period for subsoiling clay soil because these soils are always too wet at that time of the year (Weill, 2005). Another reason for subsoiling in late summer/early fall is that the following winter freeze-thaw cycles also help to break up the large clods which sometimes result from subsoiling. Heavy soils, even when compacted, are often fissured thus allowing some root and water to reach the subsoil. In such situations, subsoiling may be unnecessary (Weill, 2005).

Peat
Peat soils are elastic and are more likely to collapse and deform plastically before they become too compacted. Deformation does worsen the physical properties of the peat. Experience has shown that grasslands on peatlands that are mowed or grazed under wet conditions sometimes suffer from long-term compaction (Van den Akker et al., 2013a). The carrying capacity of peat in wet conditions is very low and, especially at the surface, the peat can be trampled on and compacted, which completely destroys the structure at the surface and greatly reduces the infiltration capacity.

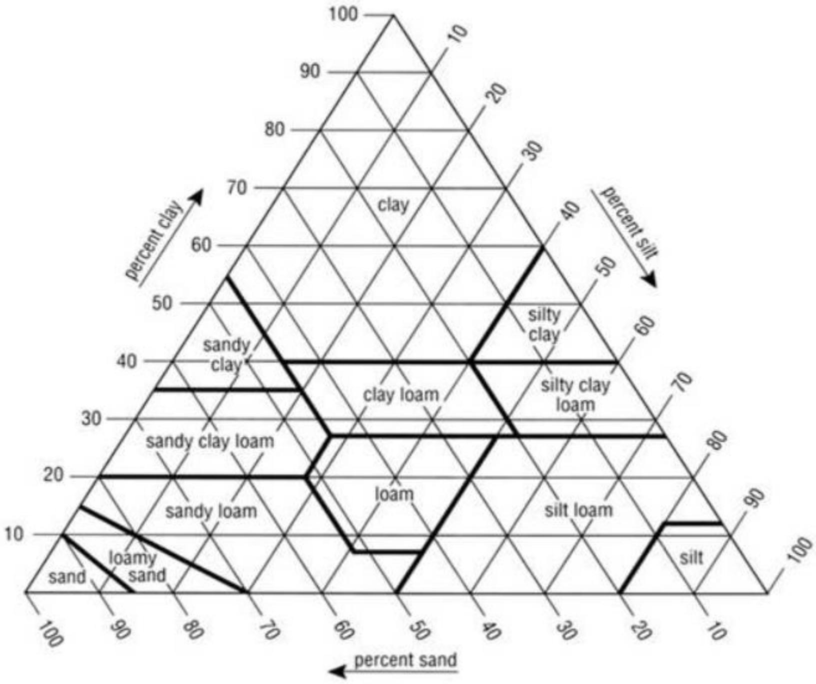

Figure 4-1 *Textural triangle. The textural triangle describes the relative proportions of sand, silt and clay in various types of soils.*
Source: http://soils.usda.gov/technical/manual/print_version/complete.html.

Table 4-1 *Applicability of recovery techniques for different soil texture types.*

Recovery technique	Coarse textured	Medium textured	Fine textured	Peat
Swelling/shrinking	--	-	++	+
Freezing/thawing	--	-	+	-
Subsoiling	-	--	+	--
Biosubsoiling	+	+	+	+

-- not applicable.
- less applicable or large risk of recompaction.
+ applicable, medium effectiveness.
++ applicable, large effectiveness.

4.2 Applicability for different climate conditions

The description of the various recovery techniques in the previous chapters indicates the field conditions (f.i. dry/wet) under which they are best applied. This section attempts to determine which field conditions can be linked to specific climatic conditions. Climate conditions could be air temperature, growing season, seasonality of rainfall, freezing periods etc. In the meta-studies on compaction by Schneider et al. (2017) and Yang et al. (2022a), as well as in our survey (Chapter 3), there is little data on the performance of recovery techniques under different climate conditions. Nevertheless, to provide some direction on the possible use of recovery techniques under different climate conditions, for two techniques (freezing/thawing and biomechanical techniques) a mapping has been made.

4.2.1 Freezing and thawing

To recover subsoil compaction by freezing and thawing, the frost will have to penetrate the soil to at least 60 cm -bs for several weeks each winter. In general, building regulations in European countries specify the depth of frost that must be taken into account during construction (for example, for the Netherlands this is 60 cm b.s., and in Sweden, it ranges from 1.0 to 2.5 m b.s.). Because the building code often assumes an extreme situation, this does not say enough about the average frost depth that occurs each year but gives an indication. In this report, we assume that in climate zones D and E of the Köppen-Geiger climate classification[1] the frost penetrates sufficiently deep into the soil to have some effect on the deeper soil structure. Climate zones D and E occur in Scandinavia, in the Alps and Pyrenees and in Central Europe (Figure 4-2).

4.2.2 Biosubsoilers

Climate and weather conditions have an effect on the effectiveness of biosubsoiling and biosubsoilers. Not all biosubsoilers will be effective in every climate condition. Excessive rainfall has a positive effect on penetration resistance but a negative effect on gas (oxygen) diffusion. A dry soil increases penetration resistance and is in this way also negative for plant growth besides water shortage for plant growth. In these conditions, mechanical subsoiling is, in most cases, a better solution than biomechanical recovery. Favorable soil conditions are probably more or less the same for plants as for earthworms.

Perennial crops have the advantage above annual crops that, for plant growth, more change to grow in favourable weather conditions that can be used to develop biomass above and below ground level. Climate change gives new opportunities for growing crops and cover crops in winter. The lack of restoration of soil physical properties by freeze and thaw can be compensated by plant roots of winter crops and cover crops. The area with warm temperate climate conditions (Cs zones Figure 4.2) will extend to the northern part of Europe in the coming decennia (Unric). And so, bio-subsoiling by plant roots will in this sense become more important in Northern Europe. The challenge is the embedding of new crops and cover crops in the crop rotation without creating plant pests and diseases.

Continental climate zones with precipitation whole year round (Cf) (Figure 4.2) are the most favourable for bio-subsoiling with plant roots of cover crops. Also, Cw (winter dry) and Cs (summer dry) can be favourable depending on the growing season in which plant growth is needed. An arid (A) or cold climate (E) gives too few opportunities for plants to develop.

The Global Agro-Ecological Zones framework (GAEZ v4 is the latest version) of FAO provides spatially distributed information on the suitability of soil and terrain and agro-climatic conditions for crop growth (ca 20 crops), among which crops suitable for biosubsoiling such as sorghum, rapeseed and alfalfa (GAEZ).

[1] https://education.nationalgeographic.org/resource/koppen-climate-classification-system/

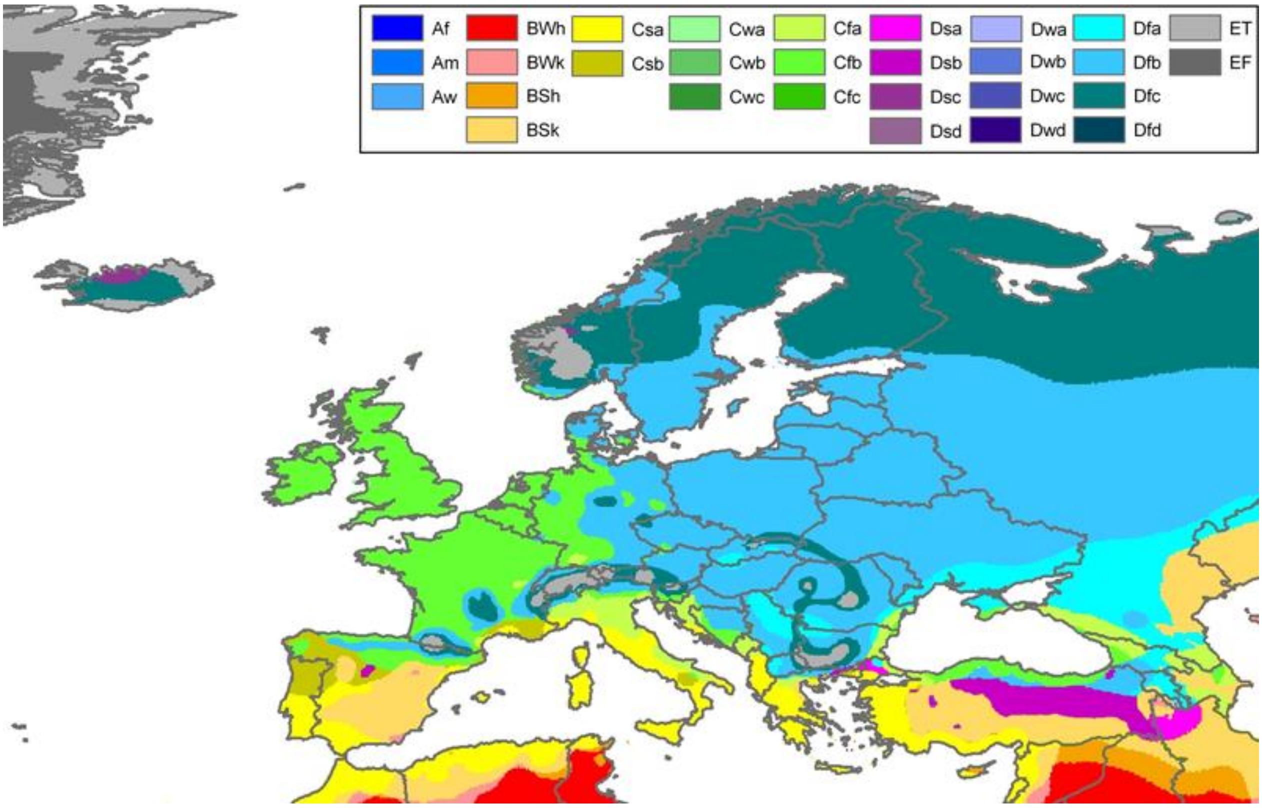

Figure 4-2 *Revised Köppen-Geiger climate type map, extract for of Europe from Peel et al, 2007.*

5 Conclusions and perspectives

5.1 Conclusions

Based on the literature review and the analysis of the recovery experiments, the following conclusions can be drawn:

The effect of individual recovery methods is difficult to determine
Recovery from soil compaction can occur through natural processes and technical interventions. Although various studies mostly study an individual process/activity, it has not been easy to determine the specific effect of a particular process/activity. This is because natural processes such as swelling/shrinking and drying/wetting cannot be avoided in compaction recovery experiments.

The effect of recovery of subsoil cannot be separated from activities in the topsoil.
In this study, the focus was on the recovery of the subsoil (25 -50 cm bs.) and less on the topsoil which is strongly influenced by tillage. The different studies show that various recovery techniques influence both the topsoil and the subsoil. This makes recovery of the subsoil inseparable from the activities taking place in the topsoil. For instance, growing a cover crop can influence keeping the soil structure open, that was created by applying subsoiling.

Swelling and shrinking as a recovery technique is only effective at clay contents > 20%.
Research on clay topsoils in particular shows that swelling and shrinking can improve the structure. This effect is also observed for subsoils, although it is not always unambiguous because several processes can be responsible for the improvement. Furthermore, it becomes clear that the swelling/shrinkage process is highly dynamic, so it is not easy to demonstrate an improvement in soil structure. The magnitude of the shrinkage/swelling process is determined by the type of clay, the clay content and the extent to which the clay can dry out sufficiently. Furthermore, the effect of the shrinkage/swelling process is influenced by tillage and compaction by heavy machinery, which reduces part of the structural improvement. The limit at which structural recovery through shrinkage can occur is generally set at a clay content of 20%. This means that the natural recovery capacity of sand and silty soils is very limited.

The effect of recovery freezing/thawing on the subsoil is limited.
Various studies show that freezing and thawing can have a positive effect on the elimination of subsoil compaction. However, the results indicate that for the deeper subsoil (> 30 cm) the effect can be limited and also that part of the possible positive effect disappears when the soil thaws again. Freezing and thawing are not possible for all areas. Firstly, frost must penetrate the ground to a great depth for several years. Tillage and the presence of cover crops influence the depth to which frost can penetrate. Furthermore, clay soils improve more due to freezing and thawing than sandy soils. This is caused by the fact that clay soils can dry out strongly as a result of freezing and thus shrink.

Subsoiling is preferred as a mechanical recovery technique
Deep tillage is often accompanied by considerable discharging, rearrangement of the soil and loss of bearing capacity. Such disturbance is highly inappropriate for protecting the subsurface from future loading and preventing its rapid recompaction. The main purpose of deep tillage for recovery subsoil compaction should be to create cracks or fissures in the compacted zone. This will allow rooting and drainage to be restored while minimizing disturbance to the remaining part of the soil profile: "fissuring without loosening." Subsoiling (loosening) should be preferred over deep ploughing and deep mixing. Drilling bore holes could be an interesting new technology.

The effect of subsoiling is highly dependent on soil moisture conditions and texture
The moisture conditions and texture of the soil are strong determinants of whether or not subsoiling restores subsoil compaction successfully in the long term or if recovery must be repeated regularly. In general, subsoiling on relatively light soils (clay < 20%) has a high risk of recompaction in the short term (3-4 years). This recompaction is, however, strongly dependent on the mechanical load after subsoiling. In general, it would be advisable not to till the soil for a few seasons after subsoiling and to drive with reduced loads. and to sow a cover crop to preserve a strong natural structure.

Biosubsoiling needs specific crops and soil conditions
Plant roots can play a role in eliminating subsoil compaction. The thicker the roots the better roots can penetrate compacted soil. Dicotyledonous crops (crucifers (radish), legumes (lucerne, clover)) are preferred because of their root structure. Sorghum, as a monocotyledonous crop is an exception. Perennial crops (grass, lucerne) have more potential to colonize deeper soil layers with their roots. Whether biosubsoiling can be effective depends on the crops used in the crop rotation and growing conditions. Crops with tap roots and perennial crops are preferred over annual crops and crops with fibrous roots.

A longer growing period means more opportunities to use favourable growing conditions. Gas exchange in the subsoil is necessary for root development. Wet soil conditions because of lack of drainage must be solved before biosubsoiling. Long dry periods increase penetration resistance and make it hard for plant roots to penetrate the soil. A climate with regular precipitation is most favorable for root growth. The presence of earthworms can help to grow in compacted soil layers as burrows of earthworms can act as biopores for plant roots. Earthworms thrive best in a relatively moist soil. Wet soil conditions and drought will make them less active.

Soils with high clay content have the greatest potential for recovery
Overall, it can be said that soils with a high clay content have the greatest potential for recovery. This applies to both the more natural solution and the mechanical solutions. For the latter, it must take place under conditions that are not too wet. For the soils with low clay content, swelling/shrinking and freezing/thawing contribute little or nothing to eliminating soil compaction. Subsoiling is possible for these soils but there is a high risk of re-compaction for the soils with a high silt fraction. Biosubsoiling seems suitable for all soils, only the effectiveness will depend heavily on soil moisture conditions.

All recovery techniques have a low recovery rate
Complete recovery of soil properties to levels prior to soil compaction is rarely observed in the experiments (n= 14) studied. In 80% of the experiments, no more than 50% recovery was found. Only in an exceptional situation was a complete recovery of soil functions found.

Efficiency of recovery depends on soil texture and climate conditions
Climate conditions can exclude recovery techniques. A continental climate with freeze and thaw on soil with >20% clay is suitable for natural recovery by swelling and shrinking of the soil. In this case, biosubsoiling can only be useful when the growing period of a crop or cover crop is long enough to develop roots in deeper soil layers when soil moisture is restored in late summer. Dry hot summers and wet warm winters on soil <20% clay cannot restore soil compaction by swelling and shrinking. In this case, winter- and cover crops can 'bio-till' the soil. In areas where cover crops do not die off during winter due to frost, ploughing or killing of the cover crops must be postponed to spring, to take maximum advantage of the root growth. Year-round precipitation is ideal for biotillage on sandy and clay soil. On clay soil >20% is a combination with swelling and shrinking of the soil possible.

5.2 Perspectives

This research has shed more light on the application of various recovery techniques for compacted soils, but also indicates that there are still large knowledge gaps. A few considerations:

Which recovery technique is preferred?
In the past, the choice was often made to mechanically crack of the compacted soil. This resulted in short-term improvement but often recompaction occurred several years later. The main disadvantage of mechanical methods is that often the complete soil structure is disturbed, which strongly reduces the mechanical strength and moisture delivery capacity. The mechanical method is useful for certain soils if executed with the right equipment and under not-too-wet conditions. However, its loosening effect will only be preserved if afterwards traffic loads are strongly reduced and cover crops with high belowground biomass are used.

However, to prevent disruption of natural structures and fast recompaction, it is better to choose more natural recovery methods. For especially some of the heavier soils, dehydration and freezing can restore the soil structure but the effect on the subsoil (> 25 cm bs.) seems generally limited. The most promising is the use of deep-rooting plants: biosubsoilers. This is because they have an effect right down to the subsoil and also have a limited negative influence on the topsoil.

More research is needed on deep-rooting crops.
More research is needed into the use of deep-rooting crops in combination with subsoiling and as a biosubsoiler. Important questions here include (a) which crops are most effective in cracking the soil and remaining soil structure, (b) what are the soil conditions (physical and chemical) under which they grow best, (c) is it enough to grow the crop for one winter season or should the crop be allowed to grow for several seasons.

How to measure recovery rate and soil compaction?
Most studies emphasize measuring soil mechanical parameters to determine recovery rate. Dry bulk density and penetration resistance are the most commonly measured parameters in this regard. However, it is known that these parameters are strongly influenced by the prevailing moisture conditions and the tillage activities performed. It might be better to also look at the conditions that influence root growth and thus directly affect crop yield. This means paying more attention to the influence a compacted layer has on air and water flow and retention. By reasoning more from the conditions of the plant and less from the soil mechanics perspective, a more precise picture of the degree of soil compaction and the effectiveness of a recovery technique can be obtained. Understanding this process properly requires more research that explicitly includes root science (see Schneider et al, 2021 and Correa et al., 2019, Figure 5-1).

Furthermore, to accurately quantify the compaction recovery rate, it is crucial to obtain (i) a baseline of the soil properties/functions before the compaction event, (ii) the state of the same soil properties/functions right after compaction, and (iii) measurements of the same variables at relevant time intervals. This will allow us to incorporate the effect of time and by extension estimate the rate of recovery. These measurements are suggested for yet-to-be-established compaction experiments. For already established long-term experiments, it is still possible to evaluate the soil functions at regular time intervals to assess the relative rate of recovery.

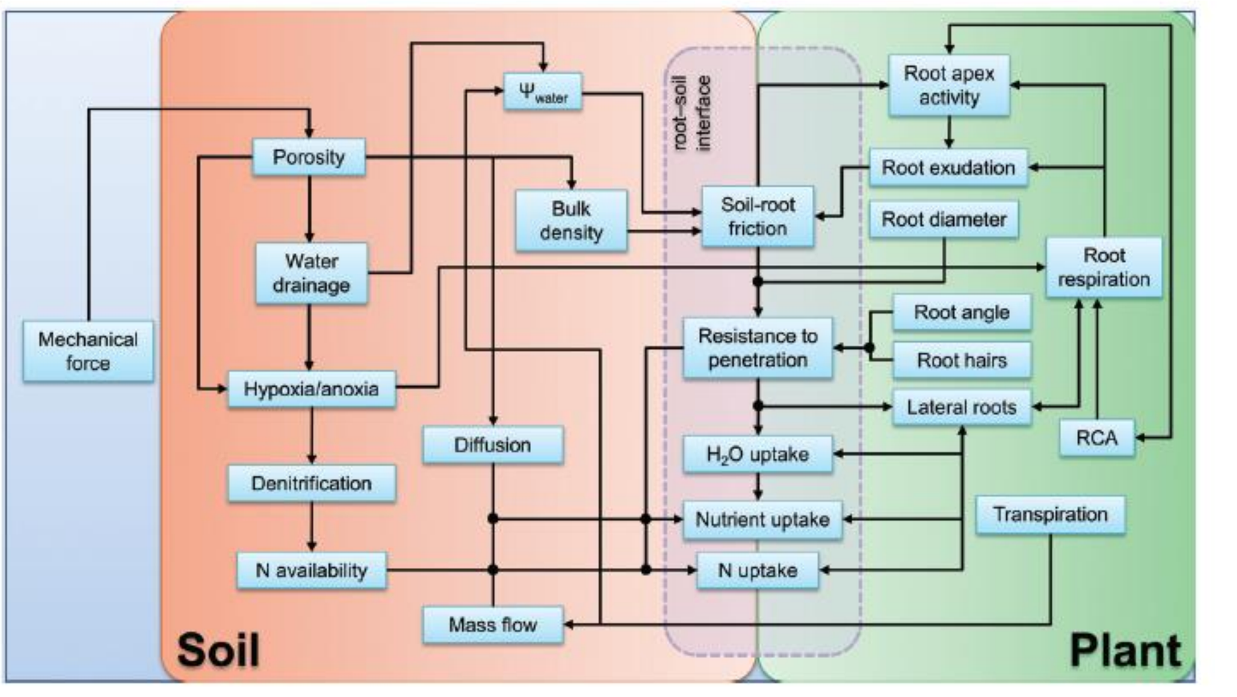

Figure 5-1 *Relational diagram of the main interactions among soil physicochemical properties and root function and structure observed under conditions of soil compaction. Ψ water, water potential; RCA, root cortical aerenchyma. The arrow (→) indicates the influence of one property on another whose interaction can be of synergistic or antagonistic nature (explained in the main text); a two-way arrow (↔) indicates a reciprocal influence between two properties; a black bullet (•) indicates converging influence between two or more properties on the following property; if two or more arrows have a point of intersection without a bullet, no direct interaction between them is indicated (Correa et al., 2019).*

Greater focus on socio-econmic aspects for recovery of soil compaction
Still in practice, much recovery of soil compaction is carried out through mechanical techniques. This is because they can be carried out relatively quickly, the machinery is available and appear to give immediate results. Techniques that require more time, new machinery or make more demands on the cultivation plan are less accepted. In order to get farmers and contractors to apply less disturbing recovery techniques, more attention should be paid to socio-economic factors. Research should be done on long-term cost-effectiveness, integration in the cropping plan and acceptance and investment of innovative techniques.

References

Akker van den, J.J.H., R. Hendriks, J. Frissel, K. Oostindie en J. Wesseling, 2013. Gedrag van verdroogde kades; ontstaan en gevaar van krimpscheuren in klei- en veenkades (in Dutch). Alterra-rapport 2473. Wageningen.

Akker van den, J.J.H., T. Hoogland en F. Stoppelenberg, 2011. Berging in kleischeuren in de Flevopolders (in Dutch). STROMINGEN 16 (2011), nummer 3.

Akker van den, J.J.H., Dure, J., Siedrink, J. and M. Heinen, 2021. Effecten van sorgum en mais op bodem en gewas op een verdichte bodem. Report 3081, https://edepot.wur.nl/545414. Wageningen University & Research.

Alakukku, L., 1996. Persistence of soil compaction due to high axle load traffic. II. Long-term effects on the properties of fine-textured and organic soils. Soil & Tillage 37 (1996) 223-238.

Andriuzzi, W. S.; Pulleman, M. M.; Schmidt, O.; Faber, J. H.; Brussaard, L. Anecic Earthworms (lumbricus Terrestris) Alleviate Negative Effects of Extreme Rainfall Events on Soil and Plants in Field Mesocosms. Plant and Soil: An International Journal on Plant-Soil Relationships 2015, 397 (1-2), 103–113 DOI: 10.1007/s11104-015-2604-4.

Bakema, G.; Bakker, G.; Cruijsen, J.; Egmond van, F.; Elsen van den, E.; Heinen, M.; Schneider, H., 2023. De invloed van bodemverdichting op de water- en luchthuishouding in de bodem en op de plantontwikkeling; Literatuuronderzoek. Wageningen. Wageningen Environmental Research. Rapport 3225. https://edepot.wur.nl/583342.

Barré, P.; McKenzie, B. M.; Hallett, P. D. Earthworms Bring Compacted and Loose Soil to a Similar Mechanical State. Soil Biology and Biochemistry 2009, 41 (3), 656–658 DOI: 10.1016/j.soilbio.2008.12.015.

Bronswijk, J.J.B., 1991. Magnitude, modeling significance of swelling and shrinking processes in clay soils. Doctoral thesis. Wageningen Agricultural University, Wageningen, The Netherlands.

Chen, G.; Weil, R. Penetration of cover crop roots through compacted soils. Plant and Soil, June 2010, Vol. 331, No. 1/2 (June 2010), pp. 31-43.

Chinn, C., Pillai-McGarry, U.P.P., 2008. Self-repair of compacted Vertisols from Central Queensland, Australia. Geoderma Volume 144, Pages 491-501.

Colombi, T., Braun, S., Keller, T., & Walter, A. (2017). Artificial macropores attract crop roots and enhance plant productivity on compacted soils. Science of the Total Environment, 574, 1283–1293. https://doi.org/10.1016/j.scitotenv.2016.07.194.

Colombi, T.; Keller, T. Developing Strategies to Recover Crop Productivity After Soil Compaction—a Plant Eco-Physiological Perspective. Soil & Tillage Research 2019, 191, 156–161 DOI: 10.1016/j.still.2019.04.008.

Correa, J., Postma, J.A., Watt, M., and Wojciechowski, T. 2019. Root system architectural plasticity and soil compaction: a review. J. Exp. Bot. 70, 6019–6034. doi:10.1093/jxb/erz383.

Cornelis, W.M., Corluy, J., Medina, H., Díaz, J., Hartmann, R., VanMeirvenne, M., Ruiz, 2006. Measuring and modelling the soil shrinkage characteristic curve. Geoderma 137, 179‐191.

Cresswell, H. P.; Kirkegaard, J. A. Subsoil Amelioration by Plant Roots - the Process and the Evidence. Australian Journal of Soil Research 1995, 33 (2), 221–221.

Çıkman, A., Monis, T., Nacar, A. S. & Vurarak, Y. (2017). Şanlıurfa Koşullarında Buğday ve Mısır Münavebesinde Geleneksel Toprak İşleme ile Anıza Doğrudan Ekim Yöntemlerinin Verime Olan Etkileri. Tarım Makinaları Bilimi Dergisi, 13 (2), 113-119. Retrieved from https://dergipark.org.tr/en/pub/tarmak/issue/34002/376577.

Çıkman, A., Monis, T., Nacar, A. S. & Vurarak, Y. (2020). Şanlıurfa Koşullarında Buğday ve Mısır Münavebesi İçin Geleneksel Toprak Işleme ve Anıza Doğrudan Ekim Yöntemlerinin Ekonomik Yönden Incelenmesi. Tarım Makinaları Bilimi Dergisi, 15 (3), 91-96. Retrieved from https://dergipark.org.tr/en/pub/tarmak/issue/52231/683098.

Dagesse, D.F., 2010. Freezing-induced bulk soil volume changes. Canadian Journal of Soil Science, 90: 389‐401.

De Boer, H.C., Deru, J.G.C., Van Eekeren, N. (2020). Sward lifting in compacted grassland: Contrasting effects on two different soils. Soil and Tillage Research 201, 104564.

Dekker, L. W., Ritsema, C. J. (1996). Variation in water content and wetting patterns in Dutch water repellent peaty clay and clayey peat soils. Catena, 28(1-2), 89-105.
Development: ESW 80436, Alterra Wageningen, 54 p.
Dörner, J., Dec, D., Peng, X., Horn, R. (2009) Change of shrinkage behavior of an Andisol in southern Chile: effects of land use and wetting/drying cycles. Soil & Tillage Research 106, 45–53.
Edwards, L.M., 2013. The effects of soil freeze–thaw on soil aggregate breakdown and concomitant sediment flow in Prince Edward Island: a review. Can. J. Soil Sci. 93 (4), 459–472.
Elkins, C. Plant roots as tillage tools, Journal of Terramechanics, Volume 22, Issue 3, 1985, Pages 177-178, ISSN 0022-4898, https://doi.org/10.1016/0022-4898(85)90094-1.
Fouli, Y., Cade-Menun, B.J., Cutforth, H.W., 2013. Freeze–thaw cycles and soil water content effects on infiltration rate of three Saskatchewan soils. Can. J. Soil Sci. 93 (4), 485–496.
GAEZ, https://gaez.fao.org/.
Geel van, C.A; Dekker, P.H.M; Groot de, W.J.M. 2009. Verbetering structuur ondergrond: verslag van veldonderzoek op een zavelgrond te Lelystad 2006-2009 Lelystad. Praktijkonderzoek Plant & Omgeving, Sector AGV.
Grant, C.D., Watts, C.W., Dexter, A.R., Frahn, B.S. 1995. An analysis of the fragmentation of remoulded soils with regard to self-mulching behaviour. Aust. J. Soil Res. 33, pp. 569–583.
Gregory AS, Watts CW, Griffiths BS, Hallett PD, Kuan HL, Whitmore AP (2009) The effect of long-term soil management on the physical and biological resilience of a range of arable and grassland soils in England.
Håkansson, I. and Reeder, R.C. (1994) Subsoil compaction by vehicles with high axle load - extent, persistence and crop response. Soil and Tillage Research 29, 277-304.
Hamilton, A. B. 1966. Freezing shrinkage in compacted clays. Can. Geotech. J. 3: 1_17.
Hamza, M. A. & Andersson, W. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil & Tillage Research* 82, 121–145.
Henry, H.A., 2007. Soil freeze–thaw cycle experiments: trends, methodological weaknesses and suggested improvements. Soil Biol. Biochem. 39 (5), 977–986.
Hoekstra, N., Joost Sleiderink, Joachim Deru, Maaike van Agtmaal, Nick van Eekeren, 2021. Hydrofobie op veengrond: oorzaken en maatregelen Rapportage van lab-experimenten in Project Integrale Bodemverbetering Feangreide. Louis Bolk Instituut.
Horn, R. & Schmucker, A. (2005). Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. *Soil & Tillage Research*, 82, 5-14.
Hu, W., Drewry, J., Beare, M., Eger, A., Müller, K. (2021). Compaction induced soil structural degradation affects productivity and environmental outcomes: A review and New Zealand case study. *Geoderma*, 395, 115035.
Jabro, J.D., Iversen, W.M., Evans, R.G., Allen, B.L., Stevens, W.B., 2014. Repeated freeze- thawcycle effects on soil compaction in a clay loam in northeastern Montana. Soil Sci. Soc. Am. J. 78 (3), 737–744.
Johannes, A., Fontana M., Köstel J., Keller T., Weisskopf P., Bragazza L. (2022). Recovery of compacted subsoil: introducing the ROCSUB project. EGU General Assembly 2022, EGU22-5230, https://doi.org/10.5194/egusphere-egu22-5230.
Joschko, M.; Diestel, H.; Larink, O. Assessment of Earthworm Burrowing Efficiency in Compacted Soil with a Combination of Morphological and Soil Physical Measurements. Biology and Fertility of Soils 1989, 8 (3), 191–196 DOI: 10.1007/BF00266478.
Keller, T., Sandin, M., Colombi, T., Horn, R. & Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil & Tillage Research*, 194, 104293.
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(4).
Keller, T., Colombi, T., Ruiz, S., et al. Soil structure recovery following compaction: Short-term evolution of soil physical properties in a loamy soil. Soil Sci Soc Am J. 2021; 85: 1002– 1020. https://doi.org/10.1002/saj2.20240.
Keller Y. and D. Or, 2022. Farm vehicles approaching weights of sauropods exceed safe mechanical limits for soil functioning Thomas. PNAS 2022 Vol. 119 No. 21.
Koeppen, http://koeppen-geiger.vu-wien.ac.at/shifts.htm.

Koolen, 1985. Processen die in de grond optreden bij diepe grondbewerking. in:Themadag effecten van diepe grondbewerking in de akkerbouw en de volleghrondsgroeneteelt, 13 december 1984, Lelystad.
Kooistra, M.J. and Boersma, O.H., 1994. Subsoil compaction in Dutch marine sandy loams: loosening practices and effects. Soil Tillage Res. 29: 237-247.
Kim, D.J., 1992. Characterization of swelling and shrinkage behaviour, hydraulic properties and modelling of water movement in a physically ripening marine clay soil. PhD thesis, Catholic University Leuven.
Leeuw, B. de, 2009. Recovery potential of compacted subsoils: A case study on loamy and clayey soils in the Netherlands, MSc thesis Land Degradation. Wageningen University.
Lipiec, J.; Horn, R.; Pietrusiewicz, J.; Siczek, A. Effects of Soil Compaction on Root Elongation and Anatomy of Different Cereal Plant Species. Soil & Tillage Research 2012, 121, 74–81 DOI: 10.1016/j.still.2012.01.013.
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.
López-Fando, C., Pardo M.T., (2009). Changes in soil chemical characteristics with different tillage practices in a semi-arid environment. Soil and Tillage Research 104: 278-284.
Kooistra, M.J. and Boersma, O.H., 1994. Subsoil compaction in Dutch marine sandy loams: loosening practices and effects. Soil Tillage Res. 29: 237-247.
Mähner, K.-T. (1999). Wachstum und Ertrag von Getreide nach mechanischer Bodenbelastund in unterschiedlichen Bearbeitungssystemen. Dissertation. Georg-August-Universität zu Göttingen.
Munkholm, L. J. & Zechmeister-Boltenstern S. (Eds.) (2021). Deliverable 2.2.1: EJP SOIL draft report on the state-of-the-art knowledge of soil research in Europe on 1. Soil carbon stocks 2. Soil degradation and soil fertility, and 3. Strategies for improved soil management.
Munkholm, L.J; Schjønning,P.; Rüegg, K. Mitigation of subsoil recompaction by light traffic and on-land ploughing: Soil response, Soil & Tillage Research, v80 n1 (2005): 149-158.
Ning, T.; Liu, Z.; Hu, H.;Li, G.; Kuzyakov, Y. Physical, chemical and biological subsoiling for sustainable agriculture, Soil and Tillage Research, Volume 223, 2022, 105490, ISSN 0167-1987, https://doi.org/10.1016/j.still.2022.105490.
Oldeman, L. R., Hakkeling, R. T. A. & Sombroek, W. G. (1991). World map of the status of human-induced soil degradation. International Soil Reference and Information Centre, Wageningen.
Olesen, J.E. and Munckholm, L.J., 2007. Subsoil loosening in a crop rotation for organic farming eliminated plough pan with mixed effects on drop yield. Soil Till. Res 94. 376-385.
Peel, M. C., Finlayson, B. L., and McMahon, T. A. 2007. Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633–1644, https://doi.org/10.5194/hess-11-1633-2007.
Pillai-McGarry, U.P.P., Collis-George, N. 1990. Laboratory simulation of the surface morphology of self-mulching and non self- mulching Vertisols. 2. Quantification of visual features. Australian Journal of Soil Research 28, 142.
Pulido-Moncada, M., Katuwal, S., Ren, L., Cornelis, W., Munkholm, L. J. (2020). Impact of potential bio-subsoilers on pore network of a severely compacted subsoil. *Geoderma* 363, 114154.
Obour, P.B., Schjonning, P., Peng, Y., Munkholm, L.J., 2017. Subsoil compaction assessed by visual evaluation and laboratory methods. Soil Till Res 173, 4-14.
Pulido-Moncada, M., Katuwal, S., Munkholm, L.J., 2022. Characterisation of soil pore structure anisotropy caused by the growth of bio-subsoilers. Geoderma 409.
Pulido-Moncada, M., Monnereau, C., Munkholm, L.J., 2021. Root-dependent recovery of pore system functionality of compacted subsoil: A field case study with bio-subsoilers in Denmark. Soil Sci Soc Am J 85(5), 1566-1577.
Rijniersce, K., 1983. A Simulation Model for Physical Soil Ripening in the IJsselmeerpolders. Rijksdienst voor de IJsselmeerpolders, Lelystad.
Sivarajan, S., Maharlooei, M., Bajwa, S.G., and J. Nowatzki, 2018. Impact of soil compaction due to wheel traffic on corn and soybean growth, development and yield. Soil & Tillage Research 175 (2018) 234-243.
Sahin, U., Angin, I., Kiziloglu, F.M., 2008. Effect of freezing and thawing processes on some physical properties of saline–sodic soils mixed with sewage sludge or fly ash. Soil Tillage Res. 99 (2), 254–260.
Sarmah, A. K., Pillai-McGarry, U. & McGarry, D. (1996). Repair of the structure of a compacted Vertisol via wet/dry cycles. *Soil & Tillage Research*, *38*, 17-33.

Schjønning, Per, Mathieu Lamandé, Valentin Crétin, and Janne Aalborg Nielsen,2017. Upper subsoil pore characteristics and functions as affected by field traffic and freeze–thaw and dry–wet treatments. Soil Research 2017 55 2334-244.

Schjønning, P., van den Akker, J. J., Keller, T., Greve, M. H., Lamandé, M. & Simojoki, A., et al. (2015). Driver-Pressure-State-Impact-Response (DPSIR) Analysis and Risk Assessment for Soil Compaction—A European Perspective. In *Advances in agronomy*. First edition (ed. D.L. Sparks), pp. 183–237. Academic Press, Amsterdam [Netherlands].

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 & Tillage Research* 174, 193–204.

Schneider, H.M., Strock, C.F., Hanlon, M.T., Vanhees, D.J., Perkins, A.C., Ajmera, I.B., et al. 2021. Multiseriate cortical sclerenchyma enhance root penetration in compacted soils. Proc. Natl. Acad. Sci. U. S. A. 118. doi:10.1073/pnas.2012087118.

H. Schulte-Karring & M. Haubold-Rosa, Subsoiling and Deep Fertilizing with New Technique as a Measure of Soil Conservation in Agriculture, Viniculture and Forestry r, SOIL TECHNOLOGY vol. 6, p. 225-237 Cremlingen 1993.

Spoor, G., Tijnink, F.G.J., Weiskopf, P., 2003. Subsoil compaction: risk, avoidance, identification and alleviation. Soil &Tillage, 73 (2003) 175-182.

Spoor, 2006. Alleviation of soil compaction: requirements, equipment and techniques. Soil use and management, volume 22, issue 2 pg 113-122.

Sun Baoyang, Feipeng Ren, Wenfeng Ding, Guanhua Zhang, Jinquan Huang, Jianming Li, Lei Zhang*, 2021.* Effects of freeze-thaw on soil properties and water erosion. Soil and water research 16, 2021 (4) 205-216.

Unger, P.W., 1991. Overwinter changes in physical properties of no-tillage soil. Soil Sci. Soc. Am. J. 55 (3), 778–782.

Unric, https://unric.org/en/climate-europe-warming-faster-than-rest-of-world-ipcc/.

Van Balen, D.J.M., Verstegen H., Hogendoorn, A. Dekkers, M.S., Van den Berg, W., (2021). Duurzaam opheffen ondergrondverdichting; Werkpakket 3 PPS Klimaatadaptatie. Wageningen Research, Rapport WPR-875.

Van Balen, D.J.M. New experiments with drilling boreholes to reduce soil compaction (in preparation). Wageningen Research.

Van den Akker, J.J.H., T. Hoogland en F. Stoppelenberg, 2011 Berging in kleischeuren in de Flevopolders. (Dutch) STROMINGEN 16 (2011), nummer 3.

Voorhees, W.B., 1983. Relative effectiveness of tillage and natural forces in alleviating wheel-induced soil compaction. Soil Sci. Soc. Am. J. 47 (1), 129–133.

Wanink, F.J., J. Alblas, H.M.G. van der Werf en J.J.H. van den Akker, 1990. Snijmaisopbrengst beïnvloed door berijding. Landbouwmechanisatie nr. 4, p 28-29.

Weill, A. (2015). A Guide to Successful Subsoiling. Le Centre d'expertise et de transfert en agriculture biologique et de proximité (CETAB+), via www.cetab.org.

Xiong, P.; Zhang, Z.; Hallett, P. D.; Peng, X. Variable Responses of Maize Root Architecture in Elite Cultivars Due to Soil Compaction and Moisture. Plant and Soil: An International Journal on Plant-Soil Relationships 2020, 455 (1-2), 79–91 DOI: 10.1007/s11104-020-04673-3.

Yang, Y., Li M., Wu J., Pan X., Gao C. and Tang D.W.S. (2022) 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. Front. Plant Sci. 12:788651.

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

Yang, P. Exploring relationships between soil compaction, amelioration and functioning, PhD thesis, Wageningen University, Wageningen, NL (2022b).

Youtube (2021). https://www.youtube.com/watch?v=Xk-RX33Nbvo,

Zhang, Z.; Peng, X. Biosubsoiling: A new perspective for sustainable agriculture, Soil and Tillage Research, Volume 206, 2021, 104844, ISSN 0167-1987, https://doi.org/10.1016/j.still.2020.104844.

Zhang, Z., Yan, L., Wang, Y., Ruan, R., Xiong, P., & Peng, X. (2022). Biosubsoiling improves soil physical properties and maize growth in a compacted Vertisol by cover crops. Soil Science Society of America Journal, 86 324–337. https://doi.org/10.1002/saj2.20368.

Annex 1 Questionnaire on soil compaction recovery methods

The questionnaire is part of the EJP Soil SoilCompaC project (https://ejpsoil.eu/soil-research/soilcompac), and the aim is to review published/unpublished data on studies that focused on compaction recovery of agricultural fields across Europe. We define compaction recovery in this context as the "sustainable restoration of soil properties / functions / crop yields / ecosystem services to their previous level (or an acceptable level) after traffic induced compaction". We would like to have data on field experiments (arable, grassland) that have focused on:(i) Subsoil compaction recovery in conventional tillage system(i) topsoil recovery in no till/conservation tillage systemsThe evaluation of recovery may involve comparisons between:•Compacted vs control plots•Measurements on the same plot - before and after recovery

1. Have you or other researchers monitored/observed compaction recovery at/in your institute/country? If yes, please proceed to Question 2.
    - YES
    - NO
2. Country
3. Name of Institution
4. Name of the experimental site
5. Soil texture (e.g., USDA) and soil class (WRB or FAO classification)
6. Climate conditions/Biogeographical region of experimental site as described at https://www.eea.europa.eu/data-and-maps/figures/biogeographical-regions-in-europe-2
    - Alpine
    - Anatolian
    - Arctic
    - Atlantic
    - Black Sea
    - Boreal
    - Continental
    - Macronesia
    - Mediterranean
    - Pannonian
    - Steppic
7. Year of initial compaction or when compaction was noticed prior to recovery initiation
8. What was the Soil depth (cm) at which compaction was observed and recovered
9. Variables measured before compaction event (crop or soil variables) -Choose all that apply
    - Bulk density
    - Penetration resistance
    - Saturated hydraulic conductivity
    - Unsaturated hydraulic conductivity
    - Infiltration rate
    - Gas/Air diffusion
    - Gas/air permeability
    - Water retention
    - Water bearing capacity
    - Other:
10. Wheel load of vehicle used for compaction
    - 1-5 Mg
    - 5-10 Mg
    - 11-15 Mg
    - 15-20 Mg
    - 20 - 25 Mg
    - >25 Mg
11. Did the experiment have non-compacted control plots?

12. Variables measured immediately after compaction or just before recovery was initiated (crop or soil variables
    - Bulk density
    - Penetration resistance
    - Saturated hydraulic conductivity
    - Unsaturated hydraulic conductivity
    - Infiltration rate
    - Gas/Air diffusion
    - Gas/air permeability
    - Water retention
    - Water bearing capacity
    - Other:
13. Type/mechanisms of compaction recovery
    - Natural (wet/dry, freeze/thaw and shrink/swell cycles)
    - Mechanical
    - Biological (roots, organisms)
    - Natural + Mechanical
    - Natural + Biological
    - Mechanical + Biological
    - All three simultaneously
    - Other:
14. Year of compaction recovery measurements (crop or soil variables)
15. Short-term (<2 years) effectiveness of recovery in terms of measured variables in Q11
    - Very low (<10% recovery of the variable)
    - Low (10-30%)
    - Medium (30-50%)
    - High (50-70%)
    - Very high (70-100%)
16. Long-term (<2 years) effectiveness of recovery in terms of measured variables in Q11
    - Very low (<10% recovery of the variable)
    - Low (10-30%)
    - Medium (30-50%)
    - High (50-70%)
    - Very high (70-100%)
17. Potential negative effects of recovery approach (e.g., drainage problems, tillage problems, less root growth, increasedsoil re-compaction risk, etc.).
18. Cost assessment of recovery method/approach for use in agricultural fields. If possible, provide a price estimate under"Other", if not choose from below.
    - Too expensive for farm level
    - Users will break even if used
    - Profitable to use
    - Other:
19. What is the technological readiness level (TRL) of the recovery approach as described in https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf
    - TRL 1 – basic principles observed
    - TRL 2 – technology concept formulated
    - TRL 3 – experimental proof of concept
    - TRL 4 – technology validated in lab
    - TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
    - TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
    - TRL 7 – system prototype demonstration in operational environment
    - TRL 8 – system complete and qualified
    - TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)
20. What is the perceived/quantified user acceptance of approach for farmers and other stakeholders?
    - Acceptable

- Not acceptable

21. How applicable is the recovery approach for other soil types?
    - Applicable
    - Not applicable
22. Provide some links to websites, peer-reviewed publications or locally published reports on the compaction recovery?

Wageningen Environmental Research
P.O. Box 47
6700 AA Wageningen
The Netherlands
T 0317 48 07 00
wur.eu/environmental-research

Report 3260
ISSN 1566-7197

The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,200 employees (6,400 fte) and 13,200 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.

To explore
the potential
of nature to
improve the
quality of life

Wageningen Environmental Research
P.O. Box 47
6700 AB Wageningen
The Netherlands
T +31 (0) 317 48 07 00
wur.eu/environmental-research

Report 3260
ISSN 1566-7197

The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,200 employees (6,400 fte) and 13,200 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.