Ministerium für Klimaschutz, Umwelt,
Landwirtschaft, Natur- und Verbraucherschutz
des Landes Nordrhein-Westfalen

Preventing Soil Compaction

Preserving and Restoring Soil Fertility

Including the Classification Key for Detection and Evaluation of Harmful Soil Compaction in the Field

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Content

1. Introduction

Agricultural soil cultivation and harvest inevitably cause slight soil compaction. Especially detrimental is soil compaction which occurs deep in the subsoil, as this compaction cannot be reversed with normal soil cultivation. Due to expected future warmer winters in Germany as a result of climate change, fewer and shorter frost periods are to be expected and with that the so-called "frost action" with its soil loosening effect will occur less frequently. This means that a natural way to loosen soil structure will be lost. Field traffic, with heavy loads on wet soils, is an especially critical contributor to severe soil compaction. With the increasing "just in time" harvest practice of farmers, this is a potential source of conflict. To address this, improved techniques to reduce soil pressure and to understand actual soil water content can be helpful.

The steady increase in weight of agricultural machinery and field traffic frequency – both have increased by three- to fourfold within the last 40 years – in combination with the technical ability to drive on increasingly wet soils, has led to ever greater compaction of our soils. This process is not restricted to Germany. About 40% of agricultural soils worldwide suffer from degradation due to soil compaction – 30 million hectares in Europe alone. In Germany, 40% of the soils in the newly-formed German states show compaction at the base of the topsoil. A study on North Rhine-Westphalian fields showed this impairment on 37% of the study sites.

Harmful soil compaction strongly reduces natural soil fertility. Therefore we need to take precautionary actions to prevent further impairment of our soils. This brochure explains harmful soil compaction together with its causes and effects. With the attached **“Classification Key for Detection and Evaluation of Harmful Soil Compaction in the Field”** it gives farmers and consultants a handy tool to recognize soil compaction and shows how to prevent and remediate soil compaction in practice.

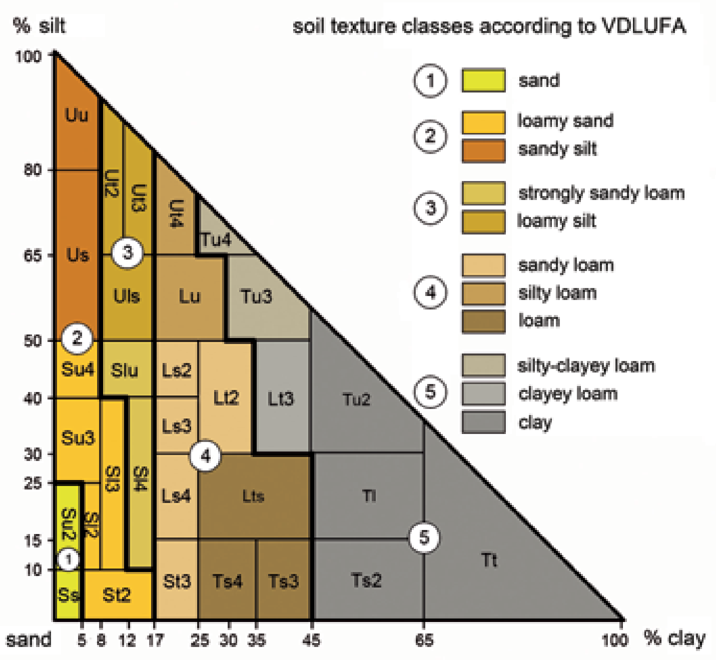
The German Federal Soil Protection Act § 17 states: “Soil compaction is to be avoided as much as possible, particularly by considering the soil texture, soil moisture and soil pressure caused by implements used for agricultural practices.”

2. The Importance of Soil Structure

The basics of soil texture

While **soil type** (e.g. Cambisol) represents the genesis, developmental stage and sequence of soil layers, **soil texture** describes the combination of differently sized mineral particles of a soil. These particles are separated by their grain size into sand, silt, and clay (soil texture groups). Loam is a mixture of all three particle sizes. Sand particles have a diameter of 2 to 0.063 mm, silt particles measure 0.063 mm to 0.002 mm and clay particles, at less than 0.002 mm in diameter, are the smallest mineral soil particles. A silt particle is 1,000 times smaller, and a clay particle 1 million times smaller than a sand grain.

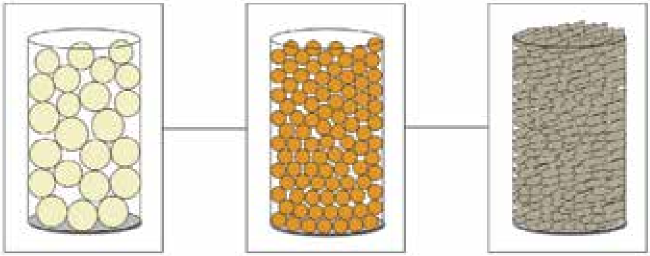
The sizes of sand, silt and clay particles affect how the soil particles are arranged relative to each other.



Pores – the spaces between soil particles – can be filled with water or air. Primary pores are those which are formed by the natural, primary arrangement of the soil particles (see figure below). Secondary pores are formed by the activities of soil organisms, such as animals, and by plant roots, as well as by swelling and shrinkage processes, etc.

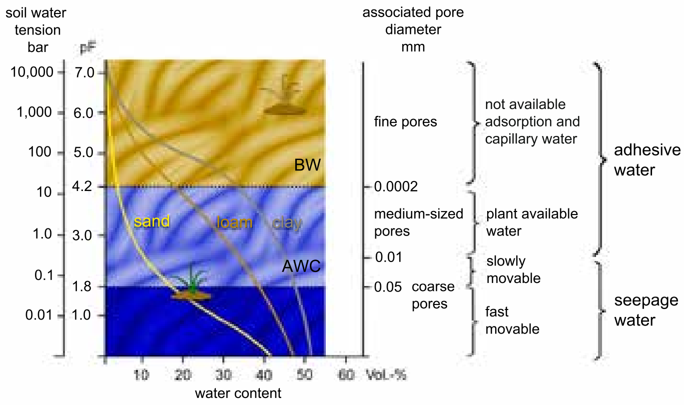
The size of the primary pores is mainly determined by the form and size of the mineral soil particles (see figure). Small clay minerals form much smaller, but numerically more, pores than the comparably large sand grains. Soils rich in silt particles have primary pore sizes between those of sandy and clayey soils and are usually rich in medium-sized pores. These pores contain plant-available water. The water inside the abundant, but fine pores in clayey soils is called “bound water“, as it is barely accessible for plants. In coarse pores, on the other hand, soil water drains very quickly into deeper layers. These pores are common in sandy soils.

The pore size distribution of a soil has an impact on the soil’s capacity both to store and to permit the flow of water. Sandy soils are bad at water storage, as the water percolates too quickly through them – their pores are



Schematic diagram of the stratification of soil particles and formation of primary pores (from left to right: sand, silt, clay) too large to allow the water molecules to stick to the soil particles (adhesive water). Clayey soils are comparably good at water storage due to the large numbers of fine pores. But their pores are unfortunately so small that the water is stuck inside them so strongly that it is almost impossible for plant roots to take it up.

The figure below illustrates this effect. When looking at the curves of the three soil texture classes at a water content of 20%, it becomes clear that the power of attraction (soil water tension/pF), with which the water is held inside the soil, differs between them. Water in a sandy soil trickles through, while the loamy soil with a high silt content holds back the water and makes it available for plants (plant available water). The water in the clayey soil, on the other hand is bound so strongly that the plant roots cannot access it (bound water).



BW = bound water, AWC = available water capactiy, pF = soil suction potential

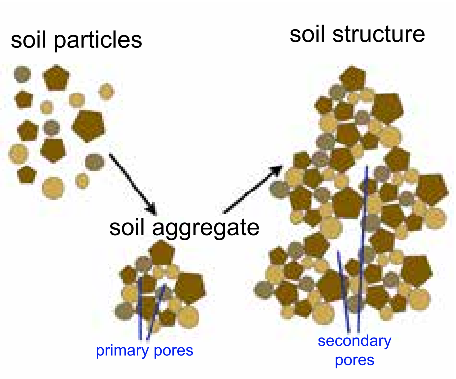
Water content/matric potential curves in sandy, loamy, and clayey soils
Source: modified after Schroeder and Blum 1992

This is why a clayey soil with 20% water content feels dry, while a silty soil with the same water content feels moist, and a sandy soils feels wet.

To be able to determine the compactability of a soil and its state of compaction, however, one needs to look at soil texture as well as soil structure.

Soil structure

The topology of a soil – **soil structure** – determines the spatial arrangement of the soil particles and has a strong influence on soil processes (compare figures pages 10 and 11). It is a mirror of the soil condition. Soil structure strongly influences its **water balance** and **air permeability** as well as **plant growth conditions**. It also determines the **load capacity** of the soil. The more stable the soil structure, the more weight a dry soil can carry without being damaged.

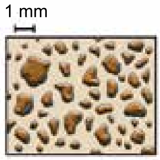


Soil science distinguishes between different types of soil structures depending on their appearance and development. Soil structure formation depends on many influencing variables, only some of which can be influenced by farmers.

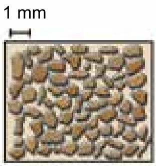
Amongst them are
- soil texture,
- clay-humus-complexes and biotic engineering (such as worm cast structures),
- physico-chemically determined drift and convergence of soil particles,
- frost action,
- shrinkage and swelling,
- timeframe of soil development, and
- soil cultivation.

Because of the forms and sizes of soil particles, **soil texture** has a crucial impact on soil structure. The tiny clay particles can, due to their structure, enter into complex chemical bonds with a wide variety of substances in soils. The relatively large surface area created by so many small particles provides many more bonding possibilities than those provided by, e.g., sand particles. Because of this phenomenon, soils rich in clay form rather stable aggregates, while sand-rich soils tend to form unstable single grain structures. Sandy soils can only form aggregated, stable structures if they are high in humus.

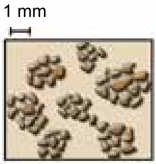
Humus, organic matter, is very important for stable soil structure, as it functions as both a sink and a source for nutrients and water and also serves as a link between soil particles. Soil management that increases the humus content can support the formation of **clay-humus-complexes** and increase **biotic engineering** by providing a good environment for soil organisms. Diverse and rich soil life in combination with sufficient organic material is therefore the key to sustainably healthy soil which can meet the demands of highly productive agriculture.



single grain structure



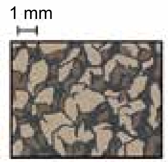
coherent structure



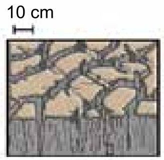
crumbly structure

Selected types of soil structure		
Name of soil structure	**Example / occurrence**	**Property**
single grain structure	sand	single grains, not connected
massive structure	iron pan, bog iron ore	solidly caked (cemented) single grains, usually with iron molecules
coherent structure	subsoil rich in silt	coherent, unstructured mass
crumbly structure	tilthy topsoil (soil favorable for cultivation)	biogenic structure with very rough, often rounded aggregates
subangular blocky structure	subsoil	lumpy edges, rough surfaces, about equally long axes
polyhedral structure	soil rich in clay	sharp edges, slick surfaces, about equally long axes
prismatic structure	clayey soil	sharp-edged, vertical structure of aggregates
platy structure	compacted soil	horizontally stratified strongly fixed soil aggre-gates
ped structure	tilth created by cultivation, medium size	similar to crumbly structure but larger aggregates
clod structure	tilth created by cul-tivation, coarse size	large, hard aggregates

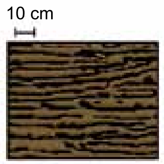
A soil rich in humus ensures a good yield under annually changing cultivation conditions. The humus content of a loess soil should be between 1.8% and 2.3% at minimum. Soil **liming** should be done to reach an optimal **pH-value** with respect to soil texture (e.g. for agricultural soils: sand pH 5.6, loamy silt pH 6.4, clayey loam pH 7.0); it has a positive influence on the soil particles and supports a loose but stable soil structure.



subangular blocky structure



prismatic structure



platy structure

Soil structure formation in the course of soil development takes place over such long time periods that it cannot be influenced by farmers in the short-term. **Shrinkage and swelling** of soil aggregates due to wetness and dryness can likewise not be influenced by farmers.

Frost wedging has helped to loosen soil structure in winter in the German climate until recently. But under a changing climate, the necessary low temperatures have seldom been reached, so that the creation of **friable tilth** due to frost wedging has become rare outside the middle and high mountain ranges.

Agriculture's major influences on soil quality are by **soil cultivation** and **field traffic**. These can damage soil structure and lead to harmful soil compaction.

Definition:
Harmful soil compaction is damage to soil structure due to cultivation practices, whereby the damage negatively affects soil regulation functions (buffer, sink and conductor for water, oxygen, nutrients and pollutants), habitat functions (microorganisms, soil animals, plants) and consequently its production functions (agricultural production, yield and costs).

3. Causes of harmful soil compaction

Harmful soil compaction is the result of an application of load that exceeds a soil's inherent stability. The excessive settling of soil (soil settling) and the impact of shear forces (shearing) that exceed the soil's inherent stability due to soil cultivation are the most common causes of harmful soil compaction.

Triggering external factors are:
- wheel load,
- contact area pressure,
- crossing frequency, and
- wheel slip/shearing.

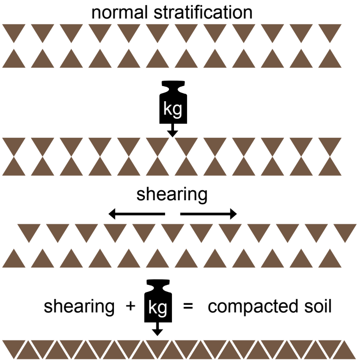
The **wheel load** determines the depth effect of the load, while the **contact area pressure** determines the impact of the load on the topsoil. In a simplified calculation, the contact area pressure is the wheel load (in kg) divided by the contact area of the wheel or conveyor belt (in cm^2). The number of crossings of a field also has a significant influence on the development of adverse soil compaction because multiple **crossings** amplify the compaction effect on the soil.

Shearing always acts in combination with the load on soil. It is a sideward movement of soil particles, which when combined with load, results in soil particle re-alignment. A common example is wheel slip during heavy towing, but shearing also occurs while slowing down. Soil particles are then kneaded and "smeared" by the tire treads. This can also occur if a non-turning tire is pulled through the soil (e.g. from transport vehicles) or if blades of implements smear through wet soil instead of breaking it up. Application of load alone also causes shearing.

The application of load creates tension in the soil which in turn impacts soil particles, resulting in displacement of the particles. In the subsoil, where wheel slip, e.g., has no impact, this is one of the main causes of compaction.

Causes of harmful soil compaction:

- soil tillage under wet soil conditions (soil smearing)
- improperly adjusted soil-working implements
- worn or incorrectly constructed blades
- driving in the furrow during ploughing
- driving on a freshly ploughed, moist field without previous re-compaction (reconsolidation roller)
- driving on moist soil
- wheel loads > 6ton on moist and > 10ton on dry soil (applied to 600 cm tire width, 1 bar internal tire pressure for moist and 2 bar internal tire pressure for dry soil)
- driving transport vehicles on the field with normal street tire equipment (truck tires on trailers, self-loading trailers, etc.)
- waterlogging caused by clogged or damaged drainage and/or natural outflows
- high livestock densities in moist weather with insufficient recovery time on the site (trampling by livestock) foster soil compactions in the upper soil centimeters



Schematic diagram of the effect of shearing (wheel slip) and load on soil particles

In addition to these external stress factors, numerous **internal factors** can influence soil compactability to a certain degree. Generally, however, **any** soil can be harmfully compacted if the superimposed load exceeds its inherent stability.

Internal factors:

- soil texture
- aggregate stability
- humus content
- bulk density
- soil structure
- pore size distribution
- lime content
- water content

Areas particularly affected:

- headlands
- wheel tracks
- field storage sites (storage stacking areas for solid dung, sugar beet field stacks, etc.)
- pastures with high livestock density, especially if soil moisture content is high
- wet areas
- base of the topsoil (often over entire field site)

Favorable conditions for harmful soil compaction:

- low humus content of the soil
- little organic material left on field after harvest as nutrient source for soil biota
- little soil life
- calcium deficiency

High **aggregate stability** – conditioned by clay-humus-complexes and biotic engineering (e.g. worm casts) – increases the load capacity of a soil. High **humus content** stabilizes mineral soils against both soil compaction and soil erosion. The lower the **bulk density** of a soil (e.g. directly after ploughing without re-compaction with a roller) and the higher the proportion of technogenic coarse pores (a result of soil tillage) the more easily soil is compacted. The **lime content** of a soil (especially Ca^{2+}-ions) also has a direct influence on soil structural stability, because lime plays a crucial role in forming clay-humus-complexes. The **water content** of a soil also affects its susceptibility to compaction. The wetter a soil, the more easily single soil particles can be moved against each other; it is much easier to compact a wet soil than a dry soil.

The depth at which harmful soil compaction is observed is indicative of its origin. Most well known is **compaction at the base of the topsoil**, also known as ploughpan. An effect of soil management, it forms directly below the horizon of soil cultivation. Tractor tires running inside the ploughed furrow have an amplifying effect as they transfer the wheel load directly onto the base of the topsoil and into the subsoil without a subsequent loosening of the soil. Harmful compaction below the zone of yearly soil loosening typically persists over many years without remediation.

Subsoil compaction is caused primarily by heavy wheel loads that are too great (e.g. harvesters with > 10t wheel load) and by recurring traffic. Due to its location in the deeper soil layers, it cannot be corrected by ordinary soil management.

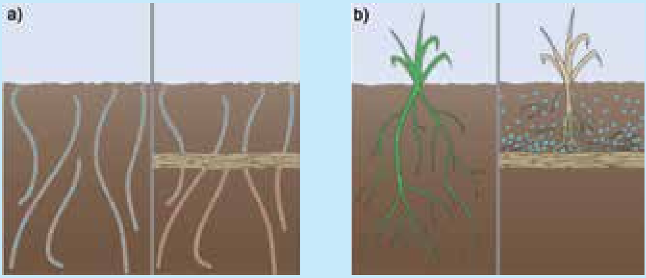
Topsoil compaction usually occurs over shorter time periods because soil cultivation in a following year can repair damage from the previous year, at least at a macroscopic level. Soil recovery on a microscopic level, however, through internal processes such as activities of soil fauna, takes much longer. Areas which experience wheel slip are especially affected.

If the inherent stability of the soil is too stressed by external factors its pore volume is reduced. Coarse pores, those which determine the water infiltration rate and air permeability, are most affected, resulting in formation of a platy structure with horizontal pores. This structure is able to carry high loads and is altered very little with the application of further loads, but soil fertility, the basis for high yields, is then lost.

4. Results of harmful soil compaction

A healthy soil has a crumbly structure and adequate organic matter, with stable pores for water transport and gas exchange and abundant biotic engineering. In comparison, a harmfully compacted soil is barely able to fulfill its function as regulator, buffer, sink and habitat for plants and animals. The consequences for both the soil and the larger ecosystem are fatal (cf. figures below and on next page)

- The **reduction of coarse pores** and interruption of vertical pores results in reduced exchange of air and water between top- and subsoil.
- The soil dries more slowly due to the slowed water infiltration rate.
- Long lasting precipitation causes **waterlogging**, resulting in root rot, oxygen deficiency and consequent death of plants and other living organisms.



Schematic diagram of conditions in uncompacted (left) and compacted soils (right)
a) capillarity
b) root growth and inhibited water infiltration

- Low water infiltration into the subsoil **reduces the replenishment rate of water storage in soil and groundwater**. Especially in regions with low precipitation, the water supply to plants is then reduced. Simultaneously the risk of flooding increases because water infiltrates the soil so slowly that most of it runs off aboveground.

- **Standing crops dry out** in dry periods – premature ripening and dying are the consequences.

- **The rooting zone is reduced**, as plant roots favor growing in coarse pores and do not penetrate compacted soil horizons effectively. The subsoil as source for nutrients and water is therefore not tapped.

- **Nutrient uptake** of plants **is reduced** both because roots cannot access the nutrients stored in dense soil aggregates and nutrients are not available; they cannot be released into the soil solution.

Reduced seepage rates (< 10 cm/day) in harmfully compacted soils cause delayed drying of the site. Optimal soil water conditions for soil cultivation are then also delayed. Because cultivation must sometimes be time-sensitive, soil condition is often a secondary consideration, however. The resulting field traffic on soils that are too wet favors harmful soil compaction, further slowing the drying of the standing crop and soil – a vicious cycle of soil degradation begins.

- **Earthworms** play an essential role in the formation of clay-humus complexes, improving soil porosity and mixing material from lower to upper soil horizons – biotic engineering – and they occur less often in harmfully compacted soils. They penetrate heavily compacted soils only sporadically.

- **Erosion of soil accelerates** with reduced water infiltration and with this **nutrients are exported**. This results in **eutrophication of surface waters** (sometimes reaching a fatal tipping point in water quality) and causing the silting or capping of loamy (silt rich) soil.

- **Nitrogen is lost** as gas from soil due to increasing soil denitrification resulting from low soil oxygen which creates reducing conditions in the soil. Nitrogen fertilizer utilization is decreased and **greenhouse gas emissions** (especially methane and nitrous oxide) are increased.

- **Plant stress increases** due to drought and waterlogging. This increases the risk of plant disease and results in **additional costs for plant protection measures**.

These factors together act against the sustainability of soil fertility, resulting in higher equipment costs to maintain the expected productivity, output, and income level of a site.

5. Recognizing harmful soil compaction

Soil compaction can be determined in various ways – it requires an accurate diagnosis.

Inspection of soil in the field is fundamental, together with the soil surface and plant cover. With the help of the **"Classification Key for Detection and Evaluation of Harmful Soil Compaction in the Field"** (attached to this brochure) it is possible to accurately examine soil in the field and to classify the observed soil conditions with regard to harmful soil compaction.

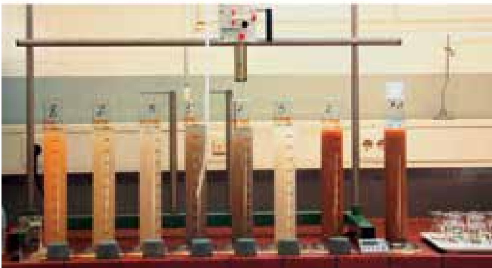
Based on **soil structure, bulk density, root growth, soil color, soil odor and coarse pores visible to the naked eye**, one can evaluate the soil condition. Aboveground **vegetation** can also be an indicator. Weak growth of cover crops can indicate soil compaction. **Algae growth** and **puddle or lake formation at the soil surface** also indicate possibly affected areas. Soil compaction can also be suspected when **insufficient nutrient turnover** – good supply but low yield – is regularly observed.

Determination of the humus content through laboratory analysis provides important information about both the soil condition and the success of soil management techniques with regard to soil fertility. The humus content in soils increases very slowly (0.1% in >10 years) – in contrast to its reduction – which is why analysis every six years is sufficient.

Penetration resistance is determined using a **manual soil penetrometer** or a **penetrologger** (see figures below). The higher the resistance, the more densely the soil is packed. The measured resistance simulates the resistance plant roots need to overcome to penetrate the soil. As the devices operate at only a small point scale, multiple measurements across a site are needed to gain reliable results. Stony ground complicates exact measurements. Penetration resistance also depends strongly on soil moisture content. Dry soil is harder and has higher penetration resistance compared to moist soil. To avoid measurement mistakes, the measurements should be done after a long rainy period followed by approximately half a day of drying. This results in a high soil moisture content (80–100% field capacity). If the penetration resistance is measured using a penetrologger, the measuring curves can be recorded. This device indicates penetration resistance of the soil in mega pascal (MPa) per centimeter soil depth. For soils with water content of 80–100% field capacity, measurement values above 2.0 MPa predict negative impacts on the crop. Above 3.0 MPa negative effects are substantial.

Instruments for measurement of the penetration resistance, from left to right: manual soil penetrometer, mechanical penetrometer, electronic penetrologger.

Physical soil laboratory of the South Westphalia University of Applied Sciences, department Soest



Further analyses can be performed in the laboratory with samples taken in the field. Depending on the research question, samples are taken in undisturbed soil cores or disturbed as for mineral nitrogen analyses.

With disturbed soil samples one can analyze, amongst others:

- pH-value,
- soil texture,
- carbonate content (lime),
- nutrients,
- particle density, and
- fine pore content.

Particle density is used to calculate the total pore volume, which is the combined space of all existing soil pores. Analyses of the soil cores provide information on:

- **Pore size distribution**
  How many coarse, medium-sized and fine pores exist in a soil? How much plant available water can be stored in a soil?
- **Air capacity**
  What is the maximum amount of air that can be held in a soil?
- **Water conductivity**
  What is the rate of seepage through a soil?
- **Air conductivity**
  How quickly can air exchange occur in a soil?

Evaluation of laboratory results in combination with field data can be done with the help of the **indicator model**. Harmful soil compaction can be recognized by means of several parameters. If the soil drops below the damage limits for air capacity (< 5%) and water conductivity (< 10 cm/day) and receives a negative rating in one out of three field structure parameters (effective bulk density, packing state, spade diagnosis) it is classified as "harmfully compacted" by the indicator model.

Further models to evaluate a soil's mechanical ability to cope with pressure are "**precompression**", "**bearing capacity quotient**", "**harmful compaction risk classes**", and "**loading index**".

6. Preserving and improving soil structure

To preserve soil fertility, one has to counteract harmful soil compaction.

Classical measures to prevent harmful soil compaction are closely related to methods of working and cultivating the soil:

- **Reduce contact area pressure** to protect topsoil by increasing the contact area of the wheel:
  - Use wide tires or flotation tires at all times (self-loading trailers, slurry tanks, manure, lime and compost spreaders, tractors, harvesters, etc.)
  - Use tire inflation pressure control systems to protect soil and provide security in road traffic at the same time. This also saves energy and reduces wheel slip.
  - Use crawler tracks on sensitive sites.
  - **Narrow "trim row crop tires" or truck tires do not belong on unpaved ground.**

- **Reduce wheel load:**
  - Preferably use towed instead of attached imple-ments.
  - Do not completely fill very large bunkers or tanks.
  - Limit the wheel load to maximum 6 ton on moist and 10 ton on dry soil.
  - Make sure to equally distribute loads on all axes.
  - Use onland ploughs in conventional farming to prevent compaction under the track of the furrow wheel in the ploughed furrow.

- **Reduce wheel slip:**
  - Use wide tires or crawler tracks with high traction (= wheel grip).
  - Reduce internal tire pressure so that tires can better adapt to the ground (0.8 bar to 1.0 bar).
  - Distribute the load equally over all axes.
  - Use four-wheel drive on a field.
  - Only drive on a field if the soil is dry.

- **Reduce the number of passes:**
  - Pool/coordinate multiple operations.
  - Confirm the necessity of operations.
  - Omit unnecessary operations.
  - Make use of the effect of previous single crops to reduce soil cultivation – oil seed rape and potatoes leave tilthy soils behind which do not need special cultivation for the following crops (cereals).

Determining soil moisture (according to The Association Of German Engineers-guideline 6101)

Condition of cohesive soils	Consistency limits and ranges	Designation
not compressible or ductile, inclined to break	stiff, solid range	stiff, solid
compressible but not ductile, due to crumbling	friable/crumbly, solid range	semisolid
compressible, difficult to knead due to stiffness	plastic range	stiff plastic
compressible, optimum kneadability/ductility		soft to plastic
compressible, barely ductile, as it is too soft	soft plasticity	pulpy to plastic
Flow limit		
not compressible or ductile, as it is fluid	Fluid range	runny

- Use existing wheel tracks also to distribute manure, lime, compost, liquid fertilizer, and slurry to keep the burdened area as small as possible.
- Use farm lanes to avoid empty drives over the field and to simplify transportation of harvested crops by vehicles equipped with road tires.

Reduce the traffic area:

- Install wheel tracks for maintenance work ➔ coordinate working widths of different implements – keyword: Controlled-Traffic-Farming (CTF).
- Increase working widths.

Associated soil moisture/suction pressure range	Compactability	Drive-ability	Workability
dry pF > 4.0	low	good	unfavorable
faintly moist pF 4.0 to > 2.7	medium	good to medium	optimal
moist pF 2.7 to > 2.1	medium, but easily kneadable	medium	very unfavorable
very moist pF 2.1 to > 1.4	high	medium to bad	very unfavorable
wet pF < 1.4	not drive-able, not workable		
very wet pF 0	not drive-able, not workable		

- **Cultivation of dry soil only:**
  - Plough preferably in summer or early autumn, because as a general rule soils have very high water content in spring and winter – ploughing frozen soil in winter is/will become less possible as climate changes. Cultivating cover crops before spring crops will be necessary.
  - Make sure that the soil is dry to the deepest point of your working depth.

- **Adjustment of soil-cultivation implements:**
  - Check the results of tillage implements after the first few meters – incorrectly adjusted blades can cause compaction. Smearing of soil is caused by poorly adjusted implements or prohibitively high soil moisture content.

In addition to classical methods of soil compaction prevention, **further measures** exist which are **related to soil fertility**:

- **Retention of crop residues on the site:**
  - Plant residues promote erosion protection and reduce siltation, which can retard plant growth especially at the germination stage.
  - The organic matter is converted partly to humus, improving soil structure and increasing soil water storage capacity.
  - Transformed (mineralized) organic matter contains valuable crop nutrients and reduces the need for mineral fertilizer use.
  - Increase soil life by leaving organic matter on the field surface.

- **Cultivation of cover crops:**
  - supports soil life,
  - introduces organic matter to the soil,
  - loosens the soil with plant roots,
  - reduces siltation and erosion via vegetation,
  - prevents leaching of nutrients over winter,
  - binds atmospheric nitrogen in the soil through the association of nitrogen fixing bacteria and legumes, which can be used by succeeding crops,
  - seed mixtures such as “Landsberger Gemenge” (italian ryegrass [Lolium multiflorum Lam.] + crimson clover [Trifolium incarnatum L.] + hairy vetch [Vicia villosa Roth.]) have a soil structure building effect through their roots, and are suitable to ameliorate soil structure.

- **Crop rotation from the perspectives of phytopathology and soil improvement:**
  - Alternate summer and winter cropping → interrupt infection pathways with nematode-resistant mustard and oil radish varieties, expanded crop rotations and increased biodiversity.
  - Cultivate cover crops.
  - Alternate broadleaf plants and grasses → interrupt infection pathways, expand crop rotations, increase biodiversity, distribute your labor effort over time.
  - Choose crops that are suited to your field conditions → sugar beets should not be planted at sites which are prone to wetness.

- **Choose organic over mineral fertilizers:**
  - Increase humus content.
  - Enhance soil biota, especially through use of solid dung and compost.

- **Guarantee optimal pH-value of the soil:**
  - Adjust your soil pH-value according to soil texture and humus content by liming to achieve a better soil structure (see chapter 2).

- **Reduce cultivation intensity:**
  - Implement systems of conservation agriculture to improve soil structure to increase soil biota and humus content and to reduce labor time and effort.
  - If you plough, plough as shallowly as possible.

Further auxiliary means exist which can be used for soil-friendly cultivation:

- **Climate data:**
  - Plan cropping patterns and cultivation time windows that fit with your prevailing climate for agriculture.

- **Weather data:**
  - Determine favorable weather conditions through, e.g., websites, agricultural services such as the weather fax of the Chamber of Agriculture in North Rhine-Westphalia, Germany to facilitate short-term, goal-oriented action planning.

- **Soil moisture measurements of the Geological Service:**
  - At a number of places in North Rhine-Westphalia, Germany, soil moisture is measured.
  - Drive equipment on and cultivate sites only under favorable soil moisture conditions.

- **Soil characteristic values:**
  - For optimal cultivation of your site, use the knowledge about soil type, soil texture, humus content, pH-value, nutrient supply, influence of groundwater and waterlogging, maximum rooting depth, etc. (e.g. from German institutions such as Agricultural Analytic and Research Institutes, Geological Service, Chambers of Agriculture, South Westphalia University of Applied Sciences)
  - Soil mapping Geological Service North Rhine Westphalia
  - Soil analyses, chemical and physical (e.g. Geological Services, Agricultural Analytic and Research Institutes, South Westphalia University of Applied Sciences)

- **Computer programs/calculation models:**
  - TASC (Tyres/Tracks and Soil Compaction) from FAT: assessment of load application by deployed machinery and implements with regard to wheel loads and contact area pressures (e.g. Swiss Research into Agriculture and Agricultural Engineering Tänikon [FAT Tänikon])

7. What to do, if the soil is already compacted?

Should the soil already be compacted, the focus is on the elimination of harmful soil compaction and determination of its causes.

The next step is to determine the dimensions of soil compaction in order to choose the most effective **remediation measures** for the case in question. The dimensions of compaction can be detected with the “Classification Key for Detection and Evaluation of Soil Compaction in the Field” (brochure attachment).

Prior to a remediation measure an expert (soil scientist) should be consulted.

Note that long-lasting soil improvement is difficult to achieve in the case of harmful compaction. Compaction as well as its reversal are both interferences with the system “soil” and should therefore not be done without serious consideration. The regeneration of the system “soil” takes several years and is not automatically finished with the completion of a remediation measure. The following applies: the more serious the harmful soil compaction, the more extensive and time-consuming the correction measures.

Different concepts can be applied in connection with compacted soils. Sometimes a combination of different measures makes sense. On agricultural sites which are influenced by waterlogging, restoring the drainage system to regulate the site’s water regime is both cause removal and correction.

Liming of a site to reach optimal pH-values (see chapter 6) is also an example of this.

For mechanical **deeper loosening**, different kinds of equipment are available. The use of any deep loosening implement requires dry soil – dry to the point of deepest tillage. Otherwise, the attempt to loosen the soil does more harm than good. Loosening measures should therefore only be performed in dry summers when soil moisture is correspondingly low. A good time is after harvest of early crops such as barley. Loosening has to be accompanied by biological stabilization in order be a long-term solution.

Rigid deep loosening tools such as **chisel subsoilers** are not very well suited due to their low loosening impact. Under unfavorable soil conditions they are harmful to the soil. This also applies to subsoilers attached to ploughs.

left: Multi-purpose breaking deep loosening implement MM 100
right: deep soil loosening implement TLG 470

Loosening tools with the most effective loosening effect are the **deep soil loosening implement** (TLG) and **multi-purpose breaking deep loosening implement** (MM). The latter is easier on more moist soils. The costs for loosening with a TLG or MM are approximately 900 to 1,200 Euro/ha depending on the application and the contractor.

Loosened soil is very unstable due to its disrupted soil structure. Applied weight load compresses the soil almost completely over the entire loosening depth, so that it is compacted again. These compactions are difficult to repair because they extend so deeply into the soil.

Remediation of harmful soil compaction therefore includes not only loosening, but necessarily also **biological stabilization** of the soil afterwards. This is achieved by seeding perennial clover grass ley (temporary grassland), alfalfa, red clover, white sweet-clover, and other plants whose roots reach deep into the soil and form a dense network that stabilizes the soil. The formation of a biologically stabilized structure that is able to withstand a load takes time if the loosening is to have a lasting positive effect. Therefore the site should be set aside or field forage should be grown with the above described plants and without turning the soil for at least three years.

In less serious cases of harmful soil compaction, remediation is possible solely by growing root active plants over a minimum time period of two years.

Integration of biological stabilization into operating procedure

For organic farms it is easier to introduce biological stabilization into the operation. Regeneration can be done in place of or through the two year cultivation of a clover grass ley, which is included in most crop rotations for N-fixation. Following this, the cultivation of phacelia for one year is suggested.

Conventional farms rarely grow clover grass ley in their crop rotations. Farms with cattle, however, can use the growth of a clover grass ley for cutting as fodder. Cropping farms can sell the growth as fodder to neighbors. Further possibilities for integration of biological stabilization into crop rotations are to register a site for set-asides or to cultivate open sowings (e.g. red clover) as certified seeds. In all cases it is possible to cultivate an undersown crop for biological stabilization after careful tillage and sowing of the previous crop. In this way the soil structure is not disturbed after harvesting of the previous crop. Harvesting must be done under dry soil conditions, however, to prevent creation of wheel tracks. A deeper loosening can then be done in the standing crop, so that the loose soil is not compacted by subsequent passages.

After remediation

After deep soil loosening one has to pay attention to the machinery used on the field. Machines and implements used during or after biological stabilization must be selected according to the following criteria:

1. **low contact area pressures** (large wheel contact area) and
2. **low wheel loads.**

The number of passages should be reduced as much as possible. Driving and cultivation must be performed under optimal soil moisture conditions. Otherwise the effect of loosening cannot be maintained.

8. Final remarks

As climate changes and petroleum resources become scarcer, the costs of harmful soil compaction with all its consequences will impose increasingly serious risks for farms. As precipitation increases in winter and decreases in spring and summer the soil will need to be able to cope with high rainfall and provide maximum water storage for dry times. Otherwise, erosion, flooding, withering or rotting of standing crops can be expected. Protection against harmful soil compaction is therefore part of a suite of strategies farms can use to adapt to a changing climate. The recognition that soil damage can have severe effects on the entire environment was acknowledged in §4 and §17 of the German Federal Soil Protection Act by the compulsory preventive and remedial duties as well as by enforcement mechanisms.

These remarks give an overview of ways to prevent harmful soil compaction. On closer inspection it is clear that measures to prevent harmful soil compaction are to some extend similar and complementary to those for erosion control.

It is therefore possible, despite changing requirements and new technologies in agriculture, to manage land in ways that are good for soil. Soil protection, also a climate adaptation strategy, is possible through a close connection of soil science and plant production knowledge on the one hand and innovative agricultural technology on the other.

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Tables to calculate the results of the field diagnosis from the "Classification Key for Detection and Evaluation of Soil Compaction in the Field"

Parameter	Factor		Class		Sum
Soil surface	1	x		=	
Penetration resistance	3	x		=	
Root growth	5	x		=	
Transitions between soil layers	3	x		=	
Decomposition state	4	x		=	
Soil color	3	x		=	
Soil odor	2	x		=	
Soil structure	5	x		=	
Consolidation state	4	x		=	
Bulk density	2	x		=	
Coarse pore content	5	x		=	
Total					

Parameter	Factor		Class		Sum
Soil surface	1	x		=	
Penetration resistance	3	x		=	
Root growth	5	x		=	
Transitions between soil layers	3	x		=	
Decomposition state	4	x		=	
Soil color	3	x		=	
Soil odor	2	x		=	
Soil structure	5	x		=	
Consolidation state	4	x		=	
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Decomposition state	4	x		=	
Soil color	3	x		=	
Soil odor	2	x		=	
Soil structure	5	x		=	
Consolidation state	4	x		=	
Bulk density	2	x		=	
Coarse pore content	5	x		=	
Total					

Parameter	Factor		Class		Sum
Soil surface	1	x		=	
Penetration resistance	3	x		=	
Root growth	5	x		=	
Transitions between soil layers	3	x		=	
Decomposition state	4	x		=	
Soil color	3	x		=	
Soil odor	2	x		=	
Soil structure	5	x		=	
Consolidation state	4	x		=	
Bulk density	2	x		=	
Coarse pore content	5	x		=	
Total					

Editor
Ministry for Climate Protection, Environment, Agriculture, Nature
and Consumer Conservancy of the country of North Rhine-Westphalia
Department of Public Relations
40190 Düsseldorf, Germany

Expert editorial office
South Westphalia University of Applied Sciences,
Agriculture Soest

MKULNV, department IV-4
Soil Protection and Contaminated Sites, Landfills

Authors
Prof. Dr. Thomas Weyer, South Westphalia University of Applied Sciences
M.Sc. Runa S. Boeddinghaus, University of Hohenheim previously South Westphalia University of Applied Sciences

Translation German to English
M.Sc. Runa S. Boeddinghaus, University of Hohenheim
M.Sc. Kathleen Regan, University of Hohenheim

Graphics
Avo Werbeagentur Soest
M.Sc. Runa S. Boeddinghaus, University of Hohenheim

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South Westphalia University of Applied Sciences

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Ministry for Climate Protection, Environment,
Agriculture, Conservation and Consumer Protection
of the State of North Rhine-Westphalia
D-40190 Düsseldorf

Telephone: 0049-211-45 66-666
Telefax: 0049-211-45 66-388

infoservice@mkulnv.nrw.de
www.umwelt.nrw.de

Classification Key for Detection and Evaluation of Harmful Soil Compaction in the Field

Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen

Fachhochschule Südwestfalen
Hochschule für Technik und Wirtschaft
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Schwannstraße 3, 40476 Düsseldorf, Germany

South Westphalia University of Applied Sciences, Agriculture Soest
Lübecker Ring 2, 59494 Soest, Germany

Authors
Prof. Dr. Thomas Weyer, South Westphalia University of Applied Sciences
M.Sc. Runa S. Boeddinghaus, University of Hohenheim previously South Westphalia University of Applied Sciences

Translation German to English
M.Sc. Runa S. Boeddinghaus, University of Hohenheim
M.Sc. Kathleen Regan, University of Hohenheim

Pictures and graphics
South Westphalia University of Applied Sciences
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Maria-Theresia Keuck, South Westphalia University of Applied Sciences

Layout
M.Sc. Runa S. Boeddinghaus, University of Hohenheim

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Application of the Classification Key

First, find a representative location on the field where you want to perform the field diagnosis.

Needed materials:

- spade
- pocket knife (minimum ca. 7 cm blade length and ca. 2 cm blade width)
- folding ruler
- mechanical penetrometer

Execution:
Follow the steps for performing a field diagnosis (see steps at right). The determination of individual characteristics for difficult cases is described below.

Perform the classification down to a depth of 30 cm (first soil monolith of the field diagnosis). Since the base of the topsoil is often compacted, it is advisable to perform the analysis of the soil status down to a depth of approximately 60 cm (second soil monolith). Existence of observable coarse pores into the subsoil is decisive for soil fertility.

Visible stratification of the soil (so called "soil horizons" – changes in soil structure, color, etc.), indicates the need to address each horizon separately. This guarantees clear identification of problem areas. A detailed, depth dependent analysis then can be performed which will clarify causes and simplify remediation decisions.

Evaluation:
To determine the total sum of scores, multiply the level number with the factor of the respective attribute. Individual products are then added to obtain the total score.

Example:

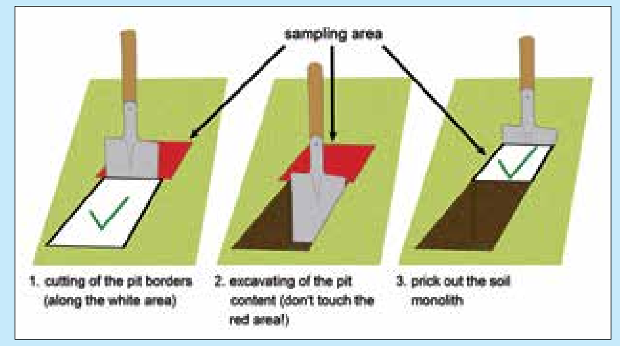
Parameter	Factor		Level		Sum
Soil surface	1	x	1	=	1
Penetration resistance	3	x	1	=	3
Root growth	5	x	1	=	5
Transitions between soil layers	3	x	3	=	9
Decomposition state	4	x	2	=	8
Soil color	3	x	2	=	6
Soil odor	2	x	1	=	2
Soil structure	5	x	1	=	5
Consolidation state	4	x	1	=	4
Bulk density	2	x	2	=	4
Coarse pore content	5	x	1	=	5
Total					**52**

If you have do not have a feature that is included in the attributes, e.g. soil surface, deduct the respective points for that attribute from the final score.

Proceeding further:
If your site does show harmful soil compaction according to this classification key, investigate the possible causes. Measures to prevent and ameliorate harmful soil compaction are shown in the companion guidebook "Preventing Soil Compaction – Preserving and Restoring Soil Fertility" of the Ministry for Climate Protection, Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia (MKULNV).

Be sure to talk to your plant production counselor about the problem and get expert advice from a soil scientist before beginning amelioration measures.

Instructions for performing a field diagnosis



Step 1:

Choose an evaluation site and cut the circumference of the pit with a spade.

Attention:
Do not step on or cut into the evaluation site with the spade.

Step 2:

Excavate the pit content initially to a depth of approximately 30 cm (one blade length of the spade). After removing and analyzing the first soil monolith, dig the pit deeper to remove additional samples (only 1 spade blade length per analysis step).

Attention:
Do not touch or damage the evaluation site with the spade during removal of soil.

Step 3:

Extend the side walls of the excavated rectangle of the site by about 10–15 cm (one hand width), and connect both lines at the end.

Step 4:

Kneel next to the pit and grab the lower part of the spade blade with one hand. The other hand secures the soil monolith as it is removed.

Step 5:

Place the spade with the soil monolith next to the pit.

Step 6:

Start soil analyses.

Penetration resistance of the soil

Grasp the mechanical penetrometer at its head end and push it vertically, evenly and slowly into the soil. You will feel the differences in resistance at depth. The greater the force needed, the denser the soil at that depth. Because if soil is very moist the penetration resistance is low, and significantly higher if soil is very dry, measurements of penetration resistance with penetrometers should only be performed at crumbly soil consistency (80–100% field capacity). This is usually the case only after long periods of rain. Penetrometers do not give accurate results during drought or if the soil is dried out, as dry soils can mimic soil compaction. As it is a point-dependent measurement, a number of punches need to be done in an area to guarantee a representative result. Within the site, specific differences between the areas "wheel track", "headland" and "core area" will occur.

Root growth

Plant roots grow preferably in easily penetrated substrate. They prefer loose soil, earthworm burrows, old root canals, cracks or fissures in soil. The denser the soil, the fewer the roots which will grow through aggregates, and the more they will favor already existing cracks. Distribution of roots therefore provides information on soil condition. If observed root growth is mostly horizontal and not vertical, as shown in the figure, soil compaction does exist.

Transitions between soil layers

In a healthy soil the transitions between topsoil and subsoil are indistinct. This is true for the structure of top- and subsoils as well as for bulk density and rooting areas (boundaries between top and subsoil horizons and soil layers within the topsoil). If a soil shows sharp boundaries between single depths, vertical matter transport is hindered. Such boundaries between single soil depths can easily be determined on a soil monolith.

Pull the blade tip of a pocket knife vertically along the sidewall of the monolith from top to bottom using a uniform pressure. If sharp boundaries between soil layers have formed (e.g. at the base of the topsoil) the soil will easily break apart all along these lines.

Soil color

Many natural and geogenic processes determine the color of a soil. Wetness from damming and groundwater also influence color, creating more or less strong and contrasting mottling of the soil, e.g. rust stains on a lighter background. Harmful soil compaction strongly affects the water balance of a soil and can thereby influence soil color. You can evaluate the areal dimensions of the mottling of your soil using the figure at bottom left (Source: Bodenkundliche Kartieranleitung, AG Boden, Hannover 2005).

areal proportion in %	notation	level	reference sample to estimate the areal proportion at the pit wall
< 1	very low	f1	1%
1 to < 2	low	f2	2%
2 to < 5	medium	f3	3% 5%
5 to < 10	high	f4	7% 10%
10 to < 30	very high	f5	15% 20% 25%
30 to < 50	extremely high	f6	30% 40% 50%

Soil structure

Excavate a rectangular soil monolith with a spade from the soil depths you plan to evaluate. Drop the monolith from a height of approximately 1 m on a hard, even surface (e.g. board, soil surface). You can then associate the resulting fragments to the types of soil structure described on the back of this key.

Consolidation state of aggregates

The degree of consolidation is similar to the soil structure, evaluated using a shatter test from approximately 1 m height. In this method the intensity of disaggregation is evaluated – the less a soil disintegrates and the bigger the single pieces, the stronger the soil cohesion. Soils rich in clay are naturally always more cohesive than sandy or silty soils. The consolidation state can be determined using examples on the back of this key.

Bulk density

Probe the soil on the untouched sidewall of your field diagnosis pit with a pocket knife using uniform pressure. The more easily the knife penetrates, the lower the bulk density. If it is not possible to drive the knife into the soil to the handle without the use of force, the soil is considered compacted. Classifications are on the back.

Coarse pore content

Uncover a horizontal, approximately 10 x 10 cm area at the depth you want to evaluate using a spade or spatula. Estimate the number and size of visible soil pores by eye, using the estimation figure from the German soil mapping instructions (Source: Bodenkundliche Kartieranleitung, AG Boden, Hannover 2005). Be aware that the continuity of pores into deeper layers are of critical importance for the soil's condition, its water balance, and aeration regime. Pores between 0.2 and 0.05 mm in diameter, however, are not visible to the naked eye, but are especially important in the subsoil. If you suspect harmful soil compaction you should have a laboratory analysis done.

				proportion of coarse pores: visible pores in the soil		
			Vol.-%	1 - < 2	2 - < 5	5 - ≤ 10
			description	low	medium	high
pore size classification			symbol	f2	f3	f4
prevailing diameter in mm	notation	symbol				
0,5 < 1	fine	gri2				
1 < 2	medium	gri3				
2 ≤ 5	coarse	gri4				

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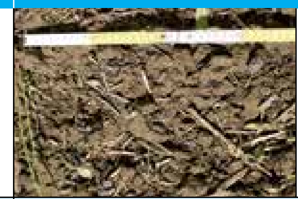
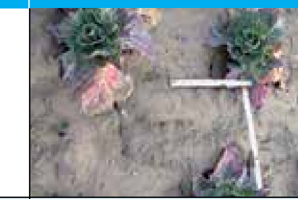
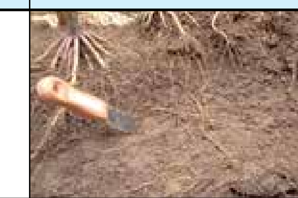
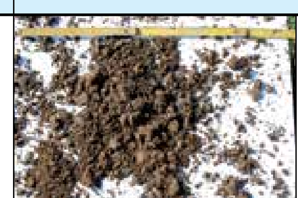
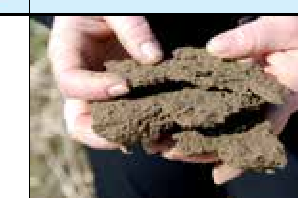
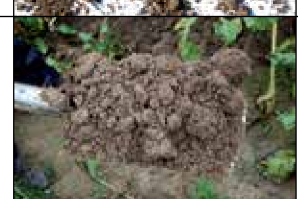
	Attribute	Factor	Level 1	Level 2	Level 3	Level 4	Level 5
Field inspection	Soil surface	1	 **crumbly texture** visible, high proportion of earthworm casts on soil surface	crumbly texture barely identifiable, low number of earthworm casts	 **no pronounced surface structure visible,** few earthworm casts	Siltation and signs of erosion visible, earthworm casts seen infrequently	 **siltation**, very slow water infiltration, often light grey to light brown surface discoloration, foul odor, green color due to algae formation
	Penetration resistance of the soil	3	low	low – medium	medium	medium – high	high
Field diagnosis 1 – evaluation with the spade	Root growth *	5	 **uniform "root network"** with many fine roots penetrating the soil horizontally and vertically, with taproots extending deep into soil	root growth exhibits a uniformly coarser network structure, roots are on average thicker	 **root growth mainly along aggregate surfaces**, coarse network, roots partially flattened	root growth in cracks between aggregates, vertical growth mostly within earthworm burrows and old root canals	 **root growth almost exclusively along burrows** and cracks, roots are coarser, more growing horizontally, fewer vertically
	Transitions between soil layers *	3	 **indistinct** no clear divisions or parting lines visible when a knife tip is drawn vertically across the soil		 **clearly visible parting lines** in the soil structure transition, e.g. transition between soil cultivation layer and lower topsoil		 **strong division** soil breaks along clear parting lines when a knife tip is drawn vertically across the soil
	Decomposition state (harvest residues, manure, etc. Consider the time span between application to field and this evaluation.)	4	 **complete decomposition** of the uniformly distributed organic material in the topsoil	only recalcitrant material is still present, finely structured material is entirely decomposed	 **uneven distribution of organic material**, coarse and medium sized material is not decomposed	decomposition takes place very slowly, "mattress formation" due to poor distribution of partially rotted organic material	 **"mattresses" form a barrier layer**, organic material rots instead of decomposing, transformation takes place very slowly
	Soil color *	3	 **uniform** brownish color of soil layer, sometimes very dark due to high humus content	small specks of black manganese and reddish iron particles, less than 2% of the area	 **significant iron (red) and manganese (black) mottles** visible (approximately 3 mm in diameter, 2–5% of the area), bleached surfaces visible	significant iron and manganese mottles (> 3 mm in diameter) on 5–10% of the area, greyish faded spots in soil	 **strong iron and manganese stains**, partially formed concretions, > 1 cm in diameter, > 10% of the area affected, strong bleaching and shades of grey, foul odor
	Soil odor	2	earthy				foul odor of hydrogen sulfide (similar to rotten eggs)
Field diagnosis 2 – evaluation with the shatter test	Soil structure *	5	 **crumbly structure** result of high biological activity, round, small aggregates with rough surfaces, many pores	**ped structure** result of soil tillage; small, firm aggregates with irregular fracture surfaces	 **clod structure** result of high soil tillage; large, firm aggregates, surfaces rounded and kneaded	clod structure with transition to platy structure	 **platy structure** result of soil compaction; horizontally arranged, very solid soil aggregates
	Consolidation state of soil aggregates *	4	 **weak/loose** soil disintegrates into many small fragments during removal		 **medium** soil disintegrates on impact into a few fragments which can be crushed by hand		 **very strong/very firm** soil barely disintegrates; coarse blocks not easily crushed by hand
Evaluations at the pit wall	Bulk density *	2	 **very low** Bd 1 (< 1.4 g/cm^3) knife can be easily pushed into the soil, soil disintegrates	**low** Bd 2 (1.4 to 1.6 g/cm^3) knife can be pushed all the way into the soil with little force	 **medium** Bd 3 (1.6 to < 1.8 g/cm^3) knife can be pushed into the soil for about half the length of the blade	**high** Bd 4 (1.8 – 2.0 g/cm^3) knife can barely be pushed into the soil	 **very high** Bd 5 (> 2 g/cm^3) only knife tip can be pushed into the soil if at all
	Coarse pore content *	5	 **high** 5–10 vol.-% of the area noticeably many earthworm burrows and old root canals		 **medium** 2–5 vol.-% of the area few earthworm burrows, old root canals, or other coarse pores		 **low** 1–2 vol.-% of the area scattered old root canals, earthworm burrows rare

Evaluation

Parameter	Factor		Level		Sum
Soil surface	1	x		=	
Penetration resistance	3	x		=	
Root growth	5	x		=	
Transitions between soil layers	3	x		=	
Decomposition state	4	x		=	
Soil color	3	x		=	
Soil odor	2	x		=	
Soil structure	5	x		=	
Consolidation state	4	x		=	
Bulk density	2	x		=	
Coarse pore content	5	x		=	
Total					

Total score 37–74 points

Your soil is sustainably fertile. It can fulfill its functions: habitat for plants and animals, regulation of material cycles, filtration of precipitation, and production of high yields. Your soil does not show compaction at the examined depths. Continue to use best practices to prevent harmful soil compaction (see measures in the brochure "Preventing Soil Compaction – Preserving and Restoring Soil Fertility").

Total score 75–111 points

Your soil shows signs of beginning cultivation-induced compaction. Revise your management practices after determining possible causes. Your soil is in a condition which will recover quickly with proper treatment. Extensive soil remediation measures are not yet necessary. Preventive measures will reduce compaction risks. Inform yourself about plant production and agricultural management strategies for prevention of harmful soil compaction (see brochure) and integrate them into your approach.

Total score 112–185 points

Your soil shows clear signs of advanced harmful compaction. The current status of your soil inhibits optimal soil functions (habitat, regulation and yield). If these conditions persist, you will have considerably higher management costs (plant protection, mineral fertilizer, energy) to maintain current yields in the long-term. Your soil cannot respond to extreme weather events, increasing the risk of harvest loss and the risk of soil erosion. Identify the causes of soil compaction on your field and eliminate them. Your management practices should be converted to those that protect your soil. The state of your soil makes remediation advisable. To discuss the best suitable techniques for your site in order to make the best management decisions, consult soil science experts (see also brochure "Preventing Soil Compaction – Preserving and Restoring Soil Fertility").

* Determination of these attributes is explained on the back.