RECOMMENDATIONS FOR SUSTAINABLE ORGANIC CROP PRODUCTION IN THE REPUBLIC OF MOLDOVA

2022

Outline

Foreword

Dear reader,

Moldova is a country with ideal conditions for field crop production. A moderate climate, high quality soils with a high percentage of the best quality chernozem types and sufficiently large blocks of land mean that, besides vineyards and orchards, Moldova is destined to be a significant force on the international market for commodities produced by modern methods on arable land.

However, favourable natural conditions are not everything, and especially the economic – political situation can lead to a poor direction in plant production. I have in mind, especially, the management of farms which mostly operate without livestock, thus without the possibility to grow soil-improving and weed-reducing fodder crops, and also without manure. This leads to a gradual decline in the natural fertility of the soil, soil erosion, a greater need for the use of industrial fertilizers and pesticides, and particularly herbicides. Here too, market demand forces farmers to grow only certain cash crops (wheat, maize, sunflowers …) without the use of appropriate crop rotation.

Conventional purchasing prices present another obstacle, as they often cannot compete with the relatively low prices on the European and global markets, which are particularly influenced by the fact that farmers in the EU, the USA and other developed countries are subsidised, and profit from farm produce is only a part of their overall income. Furthermore, they can also afford to buy more chemical inputs to improve yield. Although this may increase yield, it generally reduces the price of commodities. For economic, social and environmental reasons it is, therefore, necessary to seek alternatives which will make it possible to employ more people in the countryside, which will protect the soil and the environment, and which will deliver quality farm produce at a fair price.

The most complex solution to the aforementioned problems is provided by controlled organic farming, which provides a suitable alternative, even for bigger farms and for farms without livestock. However, the introduction of organic farming in any country necessitates to establish a whole system of regulations and instruments which organic farmers need to have for their field, just as their colleagues have in conventional farming. It begins with clear rules (in the form of laws), continues through sufficient suitable machinery and permitted agricultural inputs (species, seed, fertilizers, plant protection agents …) and ends with inspection and fair sales. The majority of these aspects are dealt with in the project *"Institutional support within organic farming in the Republic of Moldova"*, the aim of which is to transfer experience of establishing such a legally based and State-guaranteed system from the Czech Republic to Moldova. One of the components of this project is entitled *"Established system for recommendation of organic agro-technological procedures, species and varieties"*. In several regions within Moldova, on trial sites, in research institutes and on farms themselves, experimental and demonstration sites were set up with long-term trials under organic conditions. The main focus is on growing alternative crops and choosing appropriate varieties, but we also deal with issues of soil quality, nutrition and fertilization of plants, and basic agro-technological procedures, including weed control.

It is on these themes that, within the project, we have prepared this practical and modern guide for you, which summarises the latest knowledge from Europe and the USA. The author and editor of the publication, Adam Brezáni, is a young agricultural researcher, who works for the PRO-BIO company and the consulting company Czech Organics. Within the Czech Republic he is involved, among other things, in the organic demonstration farms programme.

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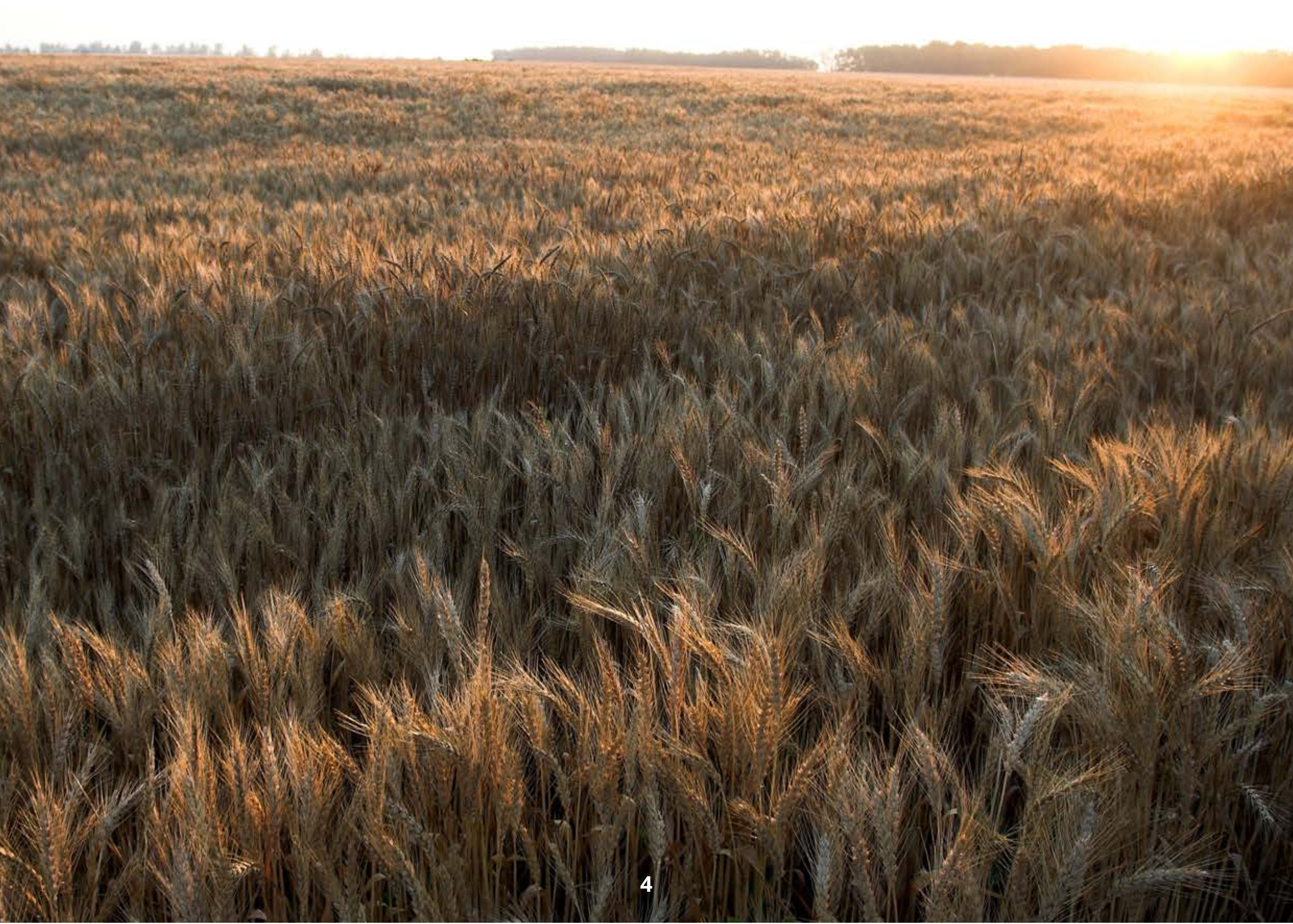
Introduction

The main aim of this publication is to demonstrate practices used in the organic sector for crop production, which can maintain sustainability and increase the market competitiveness of Moldovan organic farmers. By no means can this publication be considered as a complete guide to sustainable organic production. Many publications, guides, and information brochures are published on topics regarding organic practices. The reader can get very confused by the vast range of terminology, methods and ideas presented in each of them. This publication is an overview to explain a few basic principles of sustainable organic production by presenting practices that are successfully implemented in the sector worldwide. Particular practices were chosen to help Moldovan farmers tackle challenges such as drought, soil erosion and soil compaction to their long-term benefit. A large part of this publication focuses on soil health evaluation.



Soil

Healthy soil is required in order to grow a successful cash crop. Healthy soil means that three main aspects of soil must be kept relatively balanced. In order to properly maintain the system, one aspect cannot be compromised in favour of the other two. Soil is a complex issue and should be treated as such.

Chemical

Chemical (1) (minerals, pH, CEC). Soil is an extremely complex mixture of various chemical substances – some beneficial, some harmful and some neutral. The pH of a soil is a measure of its acidity or alkalinity, technically the hydrogen ion content of the soil's water. The main effect of pH on crop growth is that it affects the availability of many nutrients and also affects the activity of soil microorganisms. The best pH value for most crops and soils is considered to be from 6.2 to 6.8. However, the actual pH can fluctuate greatly from one day to the next, and the test distance from the roots can affect this parameter. As long as the soil test is close to the ideal range, there is no need to be overly concerned (some soil types have a more acidic, or more alkaline pH than the ideal).
Another main factor of soil chemistry that influences crop growth is the type and proportion of different nutrients and other substances in the soil. In order to be available for absorption by crop roots, nutrients must be:

Dissolved in the soil's water (in soil solution)
OR
Loosely held on soil colloids
(very small particles such as clay and humus)

Any nutrients that are tightly held on the colloids, or are part of the molecular structure of soil minerals or undecayed organic matter, will be unavailable to roots. In most soils, the great majority of nutrients are unavailable at any time. The immediate supply of available nutrients may not be sufficient at the time of peak demand for the crop. Nutrients can become available throughout the growing season, by such actions as weathering of minerals, root-produced acids, root uptake (allowing additional nutrients to go into solution), and microbial activity breaking tied-up nutrients while some root-inhabiting microbes actually feed nutrients to the roots. Certain chelatic substances found in humus and released by roots and soil microbes will make nutrients available to the roots. Nutrient supply to crops can be improved by encouraging soil life, increasing soil humus levels, using slow-release fertilizers, keeping trace elements in balance and soil calcium levels high.

Working towards a good balance of nutrients also helps to increase nutrient availability and biological activity making crops perform better in the long run. Nitrogen can be freely obtained from the atmosphere by nitrogen-fixing microbes, both on legume roots and away from roots in biologically active soil.

Problems of nutrient availability can especially occur on tight, compacted soils with poor aeration and poor drainage, which can restrict root growth and activity, as well as microbial decay of organic matter causing less nutrient release. An imbalance of nutrients can slow crop growth or result in low-quality crops and poor financial return for the grower.

Chemical Balance

Off balance:

Calcium less than 65% of CEC
Magnesium over 20% of CEC
Potassium less than 3% of CEC or more than 5%
Phosphorus less than 20 ppm (P1*)
Sulphur less than 20 ppm
N:S ratio over 15:1
pH less than 6,0 or over 7,0
Low OM (organic matter)
Low trace elements

Symptoms:

1. Hollow stems (alfalfa and brassica crops), difficult to establish, short-lived stands.
2. Poor dry-down of crops.
3. Low sugar content in plants.
4. Mineral imbalance in feed.
5. Herd health problems.
6. Crops stressed by weather.
7. Weed problems.

Balanced:

Calcium 70-85% of CEC
Magnesium 12-18% of CEC
Potassium 3-5% of CEC
Phosphorus 50 ppm (P1)
Sulphur over 25 ppm
N:S ratio 10:1
pH 6,5 - 6,8
Medium to high OM
Adequate trace elements

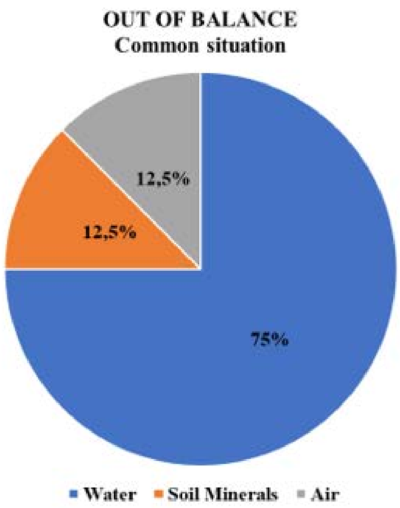
Results:

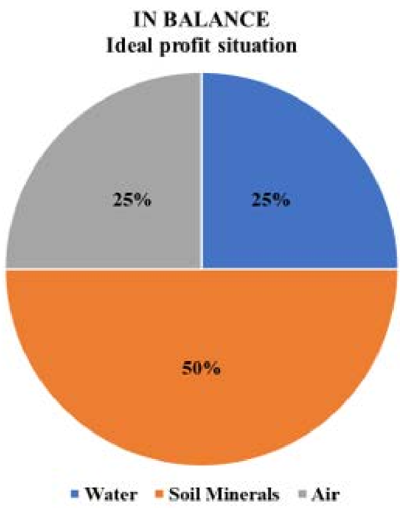
1. Solid stems (alfalfa), easy to establish, long-lived stands.
2. Good dry-down and maintained quality.
3. High sugar content.
4. Good mineral balance.
5. Healthy animals.
6. High yield; low weather stress.
7. Few weeds.

Physical

Physical (1) (aeration, aggregation, drainage). Soil structure refers to the physical condition of the soil. The ideal structure for crop growth has the tiny soil particles clumped together into larger, stable aggregates – a "cottage cheese" structure. This provides good aeration (for roots and beneficial soil organisms), rapid water intake and good drainage, moisture-holding ability, and easy root growth, while erosion is greatly reduced. Soil structure is affected by soil type and particle size (sand, silt, clay), organic matter, soil life, crop root systems, tillage, compaction, weather and soil chemistry (pH, nutrient balance, salinity). In general, higher organic matter, higher calcium levels, higher biological activity, large root systems, minimal tillage and minimal compaction are factors which foster good soil structure.

Physical Balance





Symptoms:

1. Poor water drainage; runoff.
2. Waterlogged, pot-hole problems.
3. Hardpan.
4. Ground cloddy, hard to till.
5. Poor residue decomposition.
6. Weed problems.

Causes:

1. Working soils with wrong tools at wrong time.
2. Poor management of organic matter (worked in too deep or too much).
3. Nutrient imbalance

Results:

1. Good water intake and retention.
2. Mellow soil; easy to work.
3. No crushing or hardpan.
4. Reduced erosion.
5. Large root systems.
6. Fewer weeds; less competition.

Reasons:

1. Proper tillage.
2. High humus content.
3. Abundant soil organisms.

Biological

Biological (2,3,4) (cover crops, microbes, organic matter). Soil biological processes are responsible for supplying approximately 75% of the plant-available nitrogen and 65% of available phosphorus in the soil. Maintaining biologically active soil results in more stable moisture, pH and nutrient supply. A more diverse soil community results in more flexible soils, capable of successfully growing a number of crops which are hardy in conditions of drought, low nutrients and after soil disturbance. Practices such as tillage, crop rotation and fertilizer input affect soil community abundance. Organic matter from roots, plant biomass, manure and compost provide the food energy to support the biological community. Cover crops and green manure crops increase the length of time that plants can actively grow in a soil, providing food to soil microbial populations via photosynthesis.
An idea of soil biology can be obtained from the following figures. Soils contain about 8 to 15 tons of bacteria, fungi, protozoa, nematodes, earthworms, and arthropods per hectare. A study conducted by the James J. Hoorman and Rafiq Islam at Ohio State University showed the following results (see table 1) on the relative number and biomass of microorganism species at a soil depth of 0 - 15 cm.

Table 1 - Microorganism species at 0-15 cm depth of soil (4)

Microorganisms	Number per gram of soil	Biomass (g/m^2)
Bacteria	10^8-10^9	40-500
Actinomycetes	10^7-10^8	40-500
Fungi	10^5-10^6	100-1 500
Algae	10^4-10^5	1-50
Protozoa	10^3-10^4	Varies
Nematodes	10^2-10^3	Varies

Biological Balance

Off balance
Anaerobic – decay without air

Symptoms
1. Little decay of organic matter.
2. Sour smell; anaerobic decay which produces alcohol and formaldehyde.
3. Insect and disease problems.

Balanced
Aerobic – decay with air

Results:
1. Rapid decay of organic matter.
2. Loose soil with earthy smell.
3. Earthworm presence.
4. Better crop growth.
5. Healthier plants.

Practical field soil tests

Three aspects of soil health have been described, but how can soil health be determined by the farmer? There are fairly quick, easy, and inexpensive ways to evaluate overall soil health by means of field soil tests. These tests can give indications to help narrow down potential problems. Many of these tests only require basic tools.

Visual Evaluation of Soil Structure (VESS) [5, 6]

Soil structure affects root penetration, water availability to plants and soil aeration. VESS is a quick, simple test to assess soil structure based on the appearance and feel of a soil block. It is a suitable method of evaluating the impact of tillage and management practices in different soil layers. The depth and thickness of hardpan can be determined. The size and shape of roots visually observed during VESS, can give a good indication of soil structure quality. Root disease and pests can be observed as well. Due to its flexibility and ease of use, VESS test allows a farmer to readily look at different parts of a field.

A soil block is dug out with a spade of approximately 20 cm width. A gardening spade can be used for digging, but it is preferable to use a spade with a longer blade of 35 – 45 cm (see image 1), which can penetrate the hard pan created by tillage. The depth of this hardpan is usually between 25 - 35 cm, depending on tillage practice. Soil sampling can be performed at any time of year, but preferably when the soil is still moist. Roots are best seen in an established crop or for some months after harvest.

Image 1 - Drainage spade with long and narrow blade. Source www.amazon.com

Where to sample

Select an area of uniform crop, soil colour or an area where a suspicion of a problem is raised. It is recommended that multiple samples are taken, since this can give a better overview. Attention should be given to distinguishing between field margin and headland soils, which become compacted due to machinery turning, vs. overall soil compaction caused by tillage.

Method of assessment

1. Soil block extraction (2 options)

a) Loose soil – Remove a block of soil approximately 15 – 30 cm thick directly to the full depth of the spade and place the spade along with the soil on a sheet, tray or a ground.

b) Firm soil – Dig out a hole slightly wider and deeper than the spade leaving one side of the hole undisturbed. On the undisturbed side, cut down each side of the block with the spade and remove the block as mentioned in option a).

Image 2 - Soil block sampling with a spade.
Source: https://www.sruc.ac.uk/info/120625/visual_evaluation_of_soil_structure

Examination of soil block (2 options)

a) Uniform structure – Remove any compacted soil of debris from around the block.

b) Two or more horizontal layers of different structure – Estimate the depth of each layer and prepare to score separately.

2. Breaking up the soil block

Measure block length and look for layers. Gently manipulate the block using both hands to reveal any cohesive layers or clumps of aggregates. If possible, separate the soil into natural aggregates and man-made clods (clods created by agricultural practices). Clods are large, hard, cohesive and rounded aggregates.

3. Breaking up major aggregates to confirm score

Break larger pieces apart and fragment the soil block until pieces of 1.5 – 2.0 cm are formed. Look at their shape, porosity, roots and estimate the ease of break-up. Clods that can be broken into non-porous aggregates with angular corners are indicative of poor structure and a higher evaluation score.

4. Assign a score

Match the soil to the picture category according to similarity (see table 2).

5. Confirm the score

Factors increasing the score:

- Difficulty while extracting soil block
- Larger, more angular, less porous aggregates with the presence of large worm holes
- Presence of root clusters, thickening of roots and root defection/defects
- Pockets or layers of grey soil, smelling of Sulphur and the presence of ferrous ions indicates the presence of anaerobic processes
- Aggregate fragmentation – breaking up larger aggregates 1.5 – 2.0 cm in diameter to reveal their type

6. Calculate block scores for two or more layers of differing structure

Multiply the score of each layer by its thickness and divide the result by the overall depth. Example: For a 25 cm block with 10 cm layer of loose soil (Sq1) over a more compact (Sq3) layer at 10 – 25 cm depth, the block score is (1 x 10)/25 + (3 x 15)/25 = Sq 2.2

Scoring: Scores may be attributed between Sq categories, if they have the properties of both. Scores from 1-3 are usually acceptable, whereas scores of 4 or 5 require a change of management.

Determining the calcium content

This simple determination method can be performed during the VESS. An important factor of structural soil stability is the presence of calcium and magnesium ions at sufficient levels. They allow a good connection between humus and clay particles. The application of a 10% HCl solution to the extracted soil block can determine the presence of lime particles by visible or audible popping of gas bubbles.

Table 2 – Score chart of VESS, adapted from: https://www.sruc.ac.uk/info/120625/visual_evaluation_of_soil_structure

Structure quality	Size and appearance of aggregates	Visible porosity and Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing features	Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter
Sq1 **Friable** Aggregates readily crumble between fingers	Mostly < 6 mm after crumbling	Highly porous Roots throughout the soil				The action of breaking the block is enough to reveal aggregates. Large aggregates are composed of smaller ones, held by roots. 
Sq2 **Intact** Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2 mm - 7 cm. No clods present	Most aggregates are porous Roots throughout the soil				Aggregates when obtained are rounded, very fragile → crumble very easily and are highly porous. 
Sq3 **Firm** Most aggregates can be broken with one hand	A mixture of porous aggregates from 2 mm - 10 cm; less than 30% are < 1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Porosity and roots within aggregates.				Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates. 
Sq4 **Compact** Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are < 7 cm	Few macropores and cracks All roots are clustered in macropores and around aggregates				Aggregate fragments are easy to obtain when soil is wet, cubic in shape and very sharp-edged, showing cracks internally. 
Sq5 **Very compact** Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks				A Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are usually visible. 

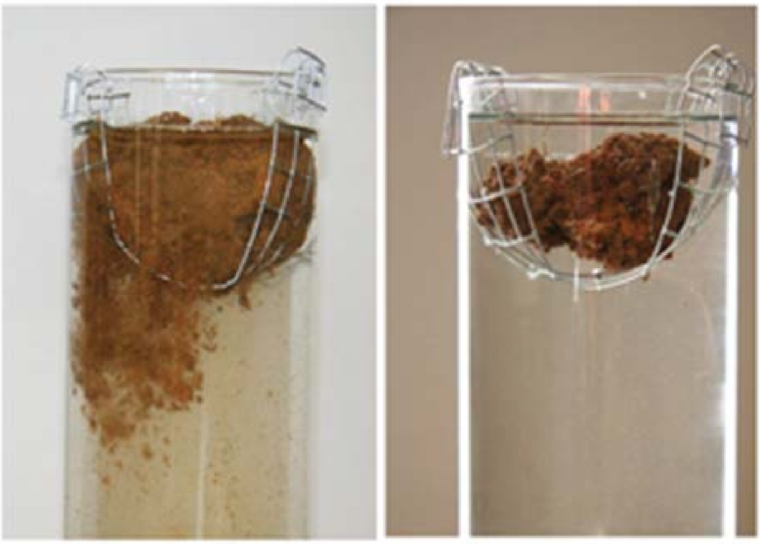
Slake test (Wet Aggregate Stability) [7, 8, 9]

The slake test enables the water holding capacity of the soil to be determined. It is also an indicator of biological activity and soil organic carbon. Well-structured soil is composed of soil aggregates.

Method of assessment

Place a lump of soil into a sieve made of chicken wire, which is hooked onto the edge of a jar full of water. Wait and observe the lump as it is submerged in water. If the soil starts falling apart without any shaking of the jar, the soil structure is poor. Healthy soils have good organic matter content. Soil with this structure can withstand vigorous shaking of the jar, while the water remains clear. Small bubbles rising to the surface from the lump of soil are also a good indicator of porous structure typical in healthy soils. These pores are held together by hydrophobic "glues" secreted by microorganisms. Several lumps of soil, collected from various parts of field, can be observed and compared at the same time, giving a better overview. The slake test can give the farmer a good indication of how the soil will perform under heavy rain and water infiltration. Healthy soils are less prone to water erosion.

Image 3 – Comparison of two soil samples from different management practices. The sample on the left clearly has a poor structure, which can indicate that the soil is more prone to water run-off.
Source: https://www.thepacker.com/news/sustainability/give-your-soil-physical-exam



Infiltration test [10]

Due to recent shifts in precipitation patterns caused by climate change, it is predicted that rain will be distributed unevenly throughout the growing season. Soils with poor structure and bad infiltration rates can have weaker water holding capacity, which will affect crops directly through poor utilization of rain water.

Method of assessment

The 150 mm x 150 mm spot chosen for conducting an infiltration test should be cleared of any debris, weeds and vegetation using a knife. Insert a plastic/metal pipe (dimensions - 150 mm diameter x 150 mm height) into the bare ground to a depth of 85 mm. Pour 450 ml of water into the cylinder and start the stopwatch. Record the time taken for water to disappear (soil surface glistering). To calculate the infiltration rate, divide 91 440 by the time in seconds, representing the number of mm infiltrated in an hour.

An example: 3 000 seconds recorded → 91 440/3 000 = 30.48 mm infiltration per hour. Storms can deliver a great amount of rainfall during an hour. 50 – 70 mm rainfall is no exception. If water is distributed mostly by rainfall during storms, the soil infiltration must be kept at a higher rate.

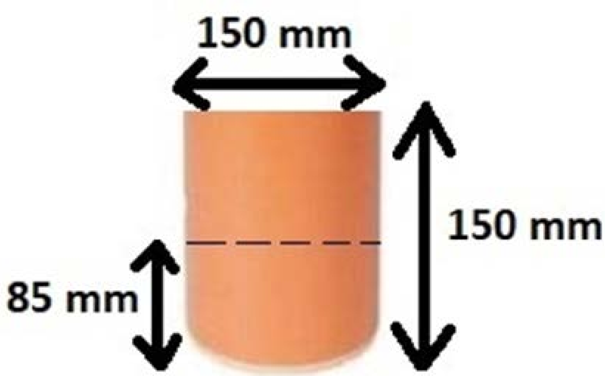


Image 4 – Plastic plumbing pipe can be used for this purpose.
Author: Adam Brezáni

Image 5 – Timing water infiltration.
Source: https://soils.vidacycle.com/soil-tests/1-3-infiltration-rate/

Simplified Nitrate Test [11, 12]

A simple nitrate test can be used for rough estimation of nitrate content in the soil. A great advantage of this method is that it is quick, easy and independent of the type of farm management (pasture or arable land) in which it can be carried out. The result is only a rough estimation, but it can help in decision making on questions such as: Is the cultivation of legumes useful at the current time? Which cover crop should be grown? How can nitrate leaching losses be prevented? On the other hand, if the soil is prone to leaching of nitrate, not only does it have an effect on potential contamination of water reservoirs or damage the environment by leaching, but as nitrate NO3 is an important part of nitrogen crop nutrition, it also means the farmer is losing money by improper nitrate utilization in the soil, most likely due to bad management practices. Nitrate that is lost could have been taken up by the cash crop, potentially resulting in greater yield.

Method of assessment

To obtain a representative soil sample → mix 10 soil samples from desired and relatively homogenous area, where the same management practices are performed. The sample should be analysed as soon as possible, or refrigerated. Prior to the nitrate test, a fingertip estimation of soil moisture is made. The naturally moist soil is sieved (hole size is about 5 mm). 100 g of sieved soil is transferred into a jar or vial. 100 ml of distilled water (contains no nitrate) is added. The jar or vial is shaken until the solution is homogenized. Afterwards the soil mixture is filtered through a folded paper filter by immersing the filter into the jar or vial. The solution slowly seeps above the filter, separating the soil solution from the clear liquid - filtrate. Nitrate is determined by means of nitrate measuring strips. These are available from laboratory suppliers or pharmacies. The measuring strips are immersed into the filtrate for one second. Both sides of the measuring strips must be covered with liquid. After one minute the colour of the strip of the outer measuring field begins to change and can be compared with the scale supplied with the test. The reading is multiplied by the factor according to soil moisture, which was tested between the fingers.

Table 3 – Soil moisture factor for soil nitrate determination (11)

Soil moisture	Fingertip soil test	Factor
12%	Crumbles between fingers	1.3
15%	Feels damp	1.4
18%	Sticks between fingers	1.5

Example: The reading indicates nitrate level 25 of damp soil (15%) → 25 x 1.4 = 35 kg/ha of NO_3

Image 6 – Steps of simple nitrate analysis.
Source: https://www.bioforschung.at/wp-content/uploads/2019/02/Einfacher_Boden_Nitrattest_Folder-2016.pdf

Soil respiration test [29]

Field CO_2 respiration test

A measurement kit for determining soil health via carbon dioxide (CO_2) from the soil. CO_2 emissions from soil are primarily a result of microbial respiration. The level of microbial activity is indicative of the amount of active organic matter that is being broken down and nutrients being released. Solvita ® is a patented measurement system, which uses a gel probe impregnated with a chemical that is sensitive to specific gas molecules and changes colour in proportion to their concentration. The colours of the gel are visually compared to a colour chart for interpretation. The Solvita field CO_2 respiration test is designed for testing fresh undisturbed soil.
On the Solvita website https://solvita.com/soil/basal-co2-guide/, it is possible to estimate the CO_2-C result and the estimated nitrogen mineralization that will occur over the course of the growing season given the temperature, moisture and length of season according to inputs.

Image 7 - Field CO2 respiration test by Solvita.
Source: https://solvita.com/co2-burst/

Laboratory CO_2 respiration test

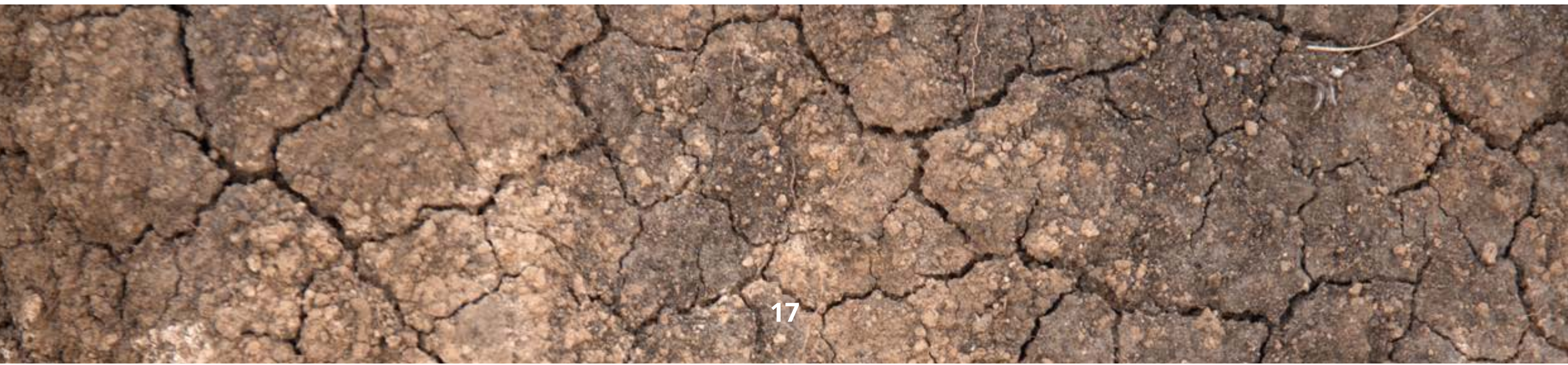
This test determines the amount of CO_2-C (ppm) released from soil microbes over the course of 24 hours after the soil sample has been dried and re-wetted (as occurs naturally in the field). This gives a measurement of the microbial biomass in the soil and relates to soil fertility and the potential for microbial activity.

Commercial laboratories have different methods for interpretation of measured CO_2. Here is an example by WARD laboratories, Inc.:

Table 4 - Soil respiration ranking table by Ward Laboratories, Inc. Source: https://www.wardlab.com/soil-respiration-test/

CO_2-C in ppm	Ranking	Implications
0-10	Very Low	Very little potential for microbial activity; slow nutrient cycling and residue decomposition; high carbon residue may last >2-3 yrs. with limited moisture; Nearly no N credit given; Additional N may be required due to microbial immobilization
11-20	Low	Minimal potential for nutrient cycling; residue management can still be a problem; Very little to no N credit given
21-30	Below Average	Some potential for nutrient cycling; residue management can still be a problem with prolonged use of high carbon crops; Little N credit given
31-50	Slightly Below Average	Low to moderate potential for microbial activity; Some N credit may be given
51-70	Slightly Above Average	Moderate potential for microbial activity; Moderate N credit may be given; May be able to start reducing some N fertilizer application
71-100	Above Average	Good potential for microbial activity; Moderate N credit may be given depending on size of organic N pool; Can typically reduce N application rates
101-200	High	High potential for microbial activity; more carbon inputs may be needed to sustain microbial biomass; moderate to high N credit from available organic N pools may be given; N fertilizer reduction can be substantial
>201	Very High	High to very high potential for microbial activity; residue decomposition may be <1 yr.; keeping the soil covered could be a problem in some systems; high potential for N mineralization and N credits from available organic N pools may be given; N fertilizer reduction can be substantial

Caution must be applied with regard to CO_2 respiration test interpretation since this may vary depending on soil type, precipitation, climatic region and management practices (manure or compost inputs, cover crops, tillage, etc.).



Chemical soil analysis [1, 13, 14, 15, 16]

The aforementioned field tests can provide many indications of overall soil health. However, field tests are insufficient for nutrient determination. Nutrient deficiency or surplus cannot be determined, and therefore properly managed. Assumptions of nutrient state can be made by looking at symptoms, such as unusual leaf coloration, wilting of young leaves, excessive pest or disease damage. However, those symptoms are usually inadequate for determining the actual state of available nutrients in the soil.

Soil tests are important for decision making with regard to what fertilizer or soil corrective agents to apply, working towards a balanced soil. The main drawback of soil tests is their interpretation. Different labs may conduct the same tests, but slight variations in equipment and protocol can affect the result. This can discourage a farmer from conducting further analysis if they cannot rely on clear interpretation of the soil test. This may lead to improper nutrient management.

There are two reasons for always using the same laboratory:

1. Soil tests from the same field can be compared from year to year,
2. Recommendations for soil correctives are consistent.

Soil tests measure soil minerals by extracting them from the sample by means of a mild acid. The soil test is limited to measuring what can be extracted by this methodology. Soil tests do not measure biological structure, or all of the minerals found in the soil. There are other important factors of soil health that will affect how the soil performs (see chapters above). Another factor to consider is pH. Soil tests are designed to work within a certain range of pH, and if the range is high or low, the soil test will not be so accurate. If the soil analysed falls into one of these two extremes, plant tissue tests or feed tests are needed to get a better idea of what minerals are available in the soil.

While soil testing has its limitations, it is still important to take soil samples every two to five years. A soil test provides an estimate of nutrient levels in the soil and can indicate whether the levels are sufficient, excessive or deficient. It is also very important to look at all of the macronutrients and micronutrients, not just NPK. A good soil test includes measurements of phosphorus, potassium, calcium, magnesium, sulphur, zinc, manganese, iron (Fe), copper and boron as well as organic matter, CEC (cation exchange capacity) and pH.

The first thing to look at on a soil report is what soil correctives are needed. Determining what soil correctives to add is simple: whatever nutrients are lacking in the soil, there is a need to add them.

Example: A soil is high in magnesium and low in calcium. Therefore, calcium is needed, not magnesium. Dolomitic limestone $CaMg(CO_3)_2$ would be the wrong choice for this soil, because no more magnesium is required. Gypsum $CaSO_4$ or high calcium limestone – calcium carbonate $CaCO_3$ would be a better choice.

It is important to deal with excesses as well as deficiencies. There are interactions between minerals in the soil, and a mineral in excess can cause as many problems as a mineral that is deficient. In order to provide a balanced diet for the crop, all mineral levels need to be in balance with each other. Closer attention needs to be paid to trace elements such as boron and sulphur, since the crop will remove them, but they do not build up in the soil.

Sampling

A field that is being sampled can be looked at as a whole, or can be divided into zones if is very heterogenous. However, zone application requires a special approach to produce a nutrient prescription map and a variable rate fertilizer applicator, which is no so common. For most farms, treating a field as a whole works well.It is recommended that about 15-20 soil samples are taken from a given field to provide one mixed representative sample from the whole field, which is managed as a unit. Edges, low parts of the field, spots with poor drainage and headlands should be avoided. A zig-zag pattern should be walked over the field to avoid following tractor tracks, crop rows, the direction of manure application and looser soil from tillage. Samples can be taken using a probe, drill, auger or a regular spade. If using a spade, it is important to avoid sampling the soil which was in direct contact with the tool, since the material the spade is made of can affect the soil analysis. Professional augers and probes are usually made of materials which do not affect the analysis.

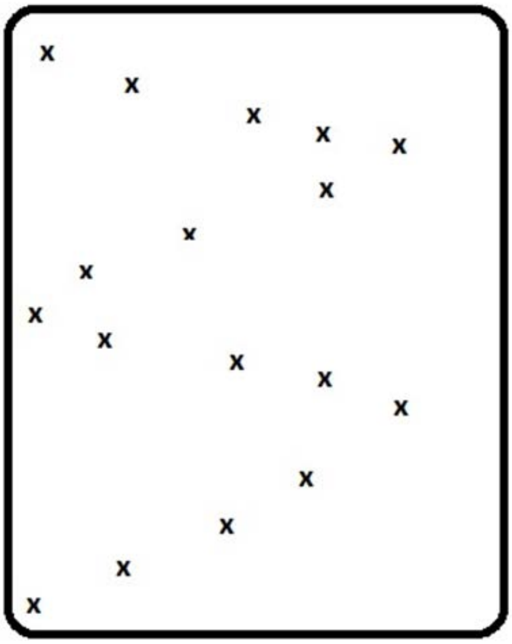
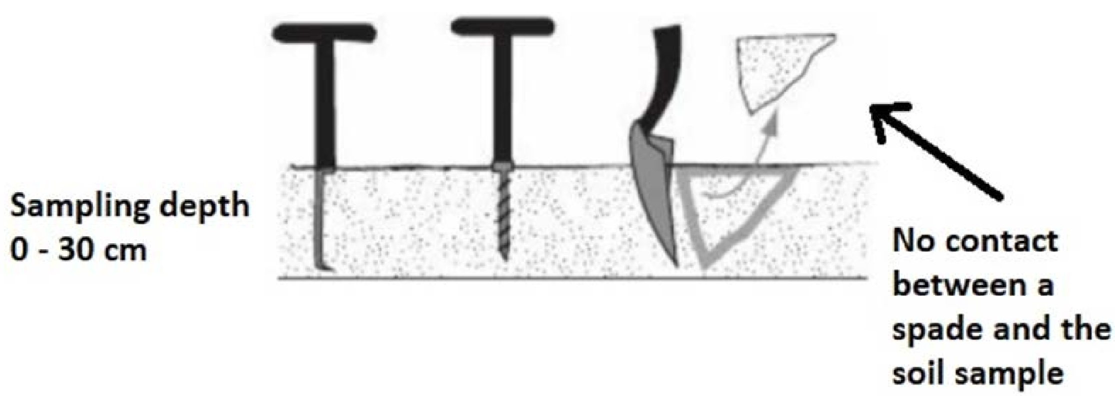


Image 8 – Zigzag pattern for soil sampling. Source: Adopted (13)

Image 9 – Sampling methods using a probe, an auger and a spade. Source: Adopted (13)



CEC: Cation Exchange Capacity

Cation exchange capacity is the ability of a soil to adsorb and exchange cations. Adsorption is the adhesion of atoms, ions or molecules from a gas, liquid or dissolved solid to a surface. Clay particles and stable organic matter (humus) both have many negative sites on their surface that can adsorb nutrients. Since opposites attract, these negative sites hold on to positively charged molecules, called cations. CEC varies between soil types. The more clay and humus a soil has, the higher its CEC, and thus the greater its ability to hold on to cations. In practical terms, this means that some soils have a greater capacity to store nutrients, while other soils have more limitations.

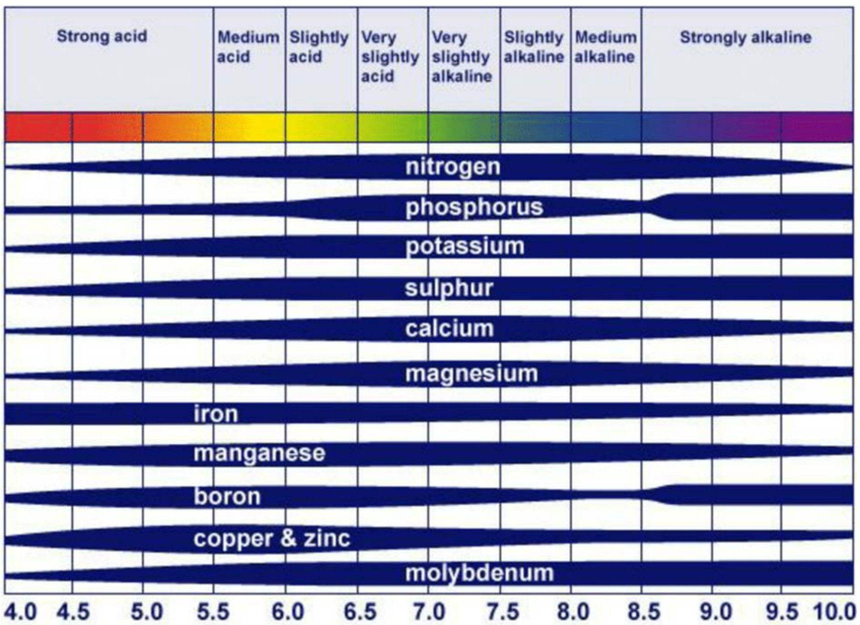
pH

A good pH range is generally between 6.8 and 7.2. This is the range where both soil fungi and soil bacteria generally live, this range also maximizes the soil minerals held by clay and humus in the soil and the ability to access these minerals.

If a soil's pH is under 6.5, lime is recommended to bring pH closer to 7.0. The quantity and type of lime used depends on soil type, what other minerals are present in the soil, and how quickly the farmer wants to change the soil pH. On a low pH soil, soil test results for minerals are often artificially high and these figures will fall after liming. Also, at low pH the availability of iron and aluminium to the plant goes up at the expense of other generally more desirable cations such as calcium and magnesium. A low pH is not beneficial to most plants in terms of energy or nutrition.

At a pH over 7.5, soil test figures may be artificially low and may not accurately reflect the level of nutrients accessible to plants in the soil. Phosphorus is often tied up in high pH soils, and phosphorus-deficient plants lack energy and are unhealthy. In addition, a high pH will affect soil life, and can mean the soil has a lower fungal population. One way of mitigating this problem is to add organic matter to the soil by growing green manure crops and by adding compost and manure to the soil.

Figure 1 – Effect of pH on nutrient availability (14)



Nitrogen

Plants need more nitrogen than any other element obtained from the soil and it is often deficient during the growing season. Nitrogen is used in many plant functions; it is part of all proteins, enzymes, DNA and many other metabolic molecules. Nitrogen can move around in the plant (it is mobile), and proportionately more is needed in the early growth stages. The symptoms of nitrogen deficiency include slow growth of tops and roots, with older leaves turning yellow then brown, especially near the centre.

Nitrogen sources:

1. Compost – can contain an average of 2%. Compost is very effective because it is a balanced plant food. It also has plant growth stimulators, and humus to improve soil structure.
2. Animal manures – poultry manure is highest in nitrogen (up to 8 percent). Manure is excellent in a shallow application in autumn so that soil organisms can convert it into forms usable by the plant.
3. Green manures – can provide 0.5 to 5% nitrogen. Legumes such as alfalfa, sweet clover, red clover, beans, etc. provide the most nitrogen. Grasses (rye, Italian rye, etc.) are also good in the growing stage. Green manures are valuable for more than nitrogen; they build soil structure, hold moisture and feed soil organisms.

Phosphorus

Phosphorus provides energy to plants, so it’s good to have sufficient levels of phosphorus in soils. However, phosphorus inputs need to be carefully regulated because runoff of this nutrient is a source of waterway pollution. Careful management of phosphorus by working inputs into the soil minimizes runoff. Once phosphorus is in the soil, it tends to tie up rather than to leach. It is very difficult to increase the phosphorus in the soil and takes a lot of input to bring phosphorus levels up. Balanced levels of available phosphorus are about 25 - 50 ppm and 50 - 100 ppm of reserve amount of phosphorus in the soil.
Caution: An adequate phosphorus level in a soil test doesn’t mean there is adequate plant-available phosphorus. It is difficult to get good phosphorus uptake without soil organic matter and healthy soil life. The best way to know if a crop has adequate phosphorus is to take a tissue test or a feed test. A tissue test reading that shows high phosphorus is a very good indicator of a healthy and biologically active soil. For example, a light soil with a CEC of five or less and low levels of organic matter that shows high levels of phosphorus in the soil test can still leave the crop short of phosphorus.

Healthy soil promotes the growth of mycorrhizae. This symbiotic fungus lives partly inside plant roots, but doesn’t act as a parasite or disease pathogen. The mycorrhizae grow slender cells out into the surrounding soil, reaching further than the plant’s root hairs. They can increase the root’s absorptive surface area by as much as 100 times.

They absorb water and nutrients that the roots could not reach, so they improve the crop's nutrition and drought resistance. In return, the root gives the fungus some of its exudate food. Mycorrhizae have been found to increase crop uptake of phosphorus, nitrogen, sulphur, zinc, copper and molybdenum, and in low-phosphorus soils, phosphorus uptake has increased.

A soil with high calcium levels is better than a low calcium acidic soil, and the natural-mined phosphorus sources containing calcium, such as rock phosphate, are a good slow-release material, especially in soils with high biological activity. Another good source of phosphorus for organic farming is manure, especially poultry manure. To utilize rock phosphate, it is recommended that it is mixed with the manure before spreading. The rock phosphate ties up nitrogen, and the mineral form of phosphorus is also made more available by microbial action.

Most of the soils' phosphorus is unavailable to the plants. Phosphate Solubilizing Microorganisms (PSM) play an important role in solubilization and mineralization of these fixed form into bio-available forms through reactions that are complex, but which provide simple solutions to P deficiency in soils. A substantial number of microbial species exhibit P solubilization capacity; these include bacteria, fungi, actinomycetes and even algae. Products consisting of PSM for organic farming are already available on the market. These products are usually in liquid form and are applied during sowing or cultivation by working them into the soil. The most popular bacteria species used are Pseudomonas and Bacillus strains, but this differs according to the manufacturer. Even though PSM can provide better P uptake for the crop, it needs to be pointed out that the positive effect varies. It is important to work the PSM into the soil, since most of them are not UV resistant. Another factor is the actual biological activity of the soil. PSM naturally occur in the soils. The less invasive tillage and more organic matter in the soil, the more PSM are naturally present in the soil. Therefore, PSM products cannot be considered as conventional fertilizers and the application of the products should be considered when the soil conditions are favourable in terms of fine structure, sufficient levels of organic matter and high biological activity, to maximize the effect.

Potassium

Potassium is needed by plants for various metabolic activities, including enzyme functions, water use, balancing electrical charges in cells, and energy release. Crops with adequate potassium grow well, have strong stalks (resist lodging), produce a lot of sugar and protein, mature early and resist diseases. Potassium is needed throughout the growing season and is mobile within the plant. Symptoms of potassium deficiency include slow growth, weak stems and the edges of older leaves turning yellow, then brown, especially between the veins.

Most soils have sufficient amounts of potassium, except sandy soils. However, over 90% of the total potassium is tied up and unavailable to plants. Some of the potassium can be released by microbial action, but usually not enough to feed the crop for a year. High levels of organic matter and calcium in the soil will reduce the fixation of potassium to clay particles.

Recommended values are 125 ppm and above 2.5% of available potassium in the soil. If the soil is close to pure sand, the potassium percentage required to reach the recommended value of 125 ppm is very high and it is difficult for the soil to hold on to that much of the nutrient. Excessive values of potassium can cause problems with animal health when feeding on forage. It is recommended that potassium is spoon-fed to the crop during the growing season.

Sources of potassium are animal manures (slow release), plant residues such as alfalfa or clover, potassium sulphate or potassium magnesium sulphate.

Calcium

Calcium has many important functions in the plant. It strengthens cell walls and is necessary for tip and root growth. It plays a key role in cellular membrane function and the transfer of material into or out of cells. It controls several metabolic enzymes and some processes in cellular respiration (energy release). It is needed for normal nitrogen use and protein production. It improves fruit quality and increases disease resistance. Calcium is extremely important for growing good legumes. Just as corn and other grasses need plenty of nitrogen to thrive, legumes need plenty of calcium. Calcium also improves soil structure, and is very important for plant growth and health. The relationship between calcium, magnesium and potassium has an influence on soil structure and plant uptake of calcium. Other benefits of relatively high soil calcium include improved soil structure (it flocculates, or clumps, colloidal particles) and stimulation of beneficial soil organisms, including nitrogen-fixing bacteria and earthworms. With good biological activity, organic matter decay is increased, nutrient release improved, and humus levels increased. Over all, crop growth and quality usually improve. Plant uptake of other elements also increases, giving a more nutritious crop.

Calcium is tied up to the clay particles resulting in a higher amount in soils that are high in clay rather than sand. The recommended base saturation is 70 – 85% of calcium. Even in high pH soils with adequate calcium soil test readings, supplementation with extra calcium is a good and worthwhile investment. Supplementary calcium in this case can come from gypsum (calcium sulphate) or granulated calcium with high soluble calcium levels.

Calcium sources:

1. High-calcium lime (calcium carbonate) – less than 3% magnesium, plus small amounts of trace elements. Raises pH, low solubility, best worked into upper soil under acidic soil conditions.
2. Dolomitic lime (calcium magnesium carbonate, dolomite) – raises pH, low solubility, best worked into upper soil under acidic soil conditions. Not always an effective plant source of calcium and a poor source of calcium in high-magnesium soils.
3. Granulated cretaceous limestone – raises pH, high solubility, very high amount of total calcium. It is a more expensive source of calcium. Granules make it easier to spread using conventional fertilizer spreaders. Spreading isn't affected by wind.
4. Gypsum (calcium sulphate) - moderately low solubility, best worked into upper soil. Supplies both calcium and sulphur. It doesn't raise pH, therefore good for adding calcium to high pH soils. Should not be used on low pH soils, or if the percentage base saturation of calcium is below 60%.
5. Rock phosphate – contains phosphorus as well. Low solubility and doesn't raise pH. Best worked into upper soil.

Magnesium

Magnesium is part of the plant's chlorophyll molecule, which makes it extremely important for growth and energy production. It is also important for protein production and enzyme function in plants. While it is very important to have sufficient magnesium in the soil, too much magnesium can also cause soils to become tight and can limit plant uptake of calcium and potassium. Recommended values of magnesium are 12 – 20% of saturation in a healthy soil.

Most soil magnesium is tied up in minerals. Excessive levels of calcium, potassium or sodium can reduce plant uptake of magnesium, some soils may not supply an adequate amount to the crop. This deficiency is typical for sandy soils with low CEC. High magnesium levels are undesirable, not only because they exclude calcium, but they may also lead to clay particles binding together, leading to crusted or tight soils. Both magnesium and sodium ions tend to break down soil structure, while calcium improves it.

Magnesium sources:

1. Dolomitic lime (calcium magnesium carbonate, dolomite) – Low solubility, not always an effective magnesium source. It raises pH.
2. Potassium magnesium sulphate – Good solubility, a good fast-release source of magnesium, potassium and sulphur.
3. Magnesium sulphate – Very soluble, a good fast-acting material in foliars.
4. Magnesium oxide – High solubility with lower cost. It doesn't raise pH.

Sulphur

Sulphur is integral to protein production in plants, so it is very important to have sufficient levels in the soil. It is needed for chlorophyll formation, root growth and nitrogen-fixing root nodule bacteria. Sulphur is an anion (negatively charged particle), so it doesn't adhere to soil particles and is prone to leaching. Low sulphur levels (below 15 ppm) indicate that sulphur should be added. High sulphur levels (above 20 ppm) can indicate subsoil compaction, low rainfall, or a recent sulphur application. Because sulphur leaches, it always needs to be included in the fertilizer program. It is recommended that at least 25 kg of sulphur in sulphate form ("sulphate sulphur" means in a form like calcium sulphate, magnesium sulphate, potassium sulphate, etc.), is applied per hectare per year. Sulphur is known as a secondary element, but most crops take up about as much sulphur as they do phosphorus.

Sources of sulphur are magnesium sulphate, potassium sulphate, calcium sulphate, animal manures and plant residues (sulphur content varies depending on the material of residues).

Boron

Boron, like sulphur, is an anion and prone to leaching. It aids calcium utilization in plants — so insufficient amounts can lead to problems in plant growth and health. The bottom line for boron is 2 ppm. As with sulphur, boron needs to be part of an annual fertilizer program. Sodium borate is a good source of this micronutrient.

Zinc

Zinc is very important for photosynthesis, so it is important to maintain adequate levels of this mineral in the soil. If zinc falls below 5 ppm it is recommended that more is added. Zinc levels also need to be higher if phosphorus levels are very high. A 10:1 ratio of phosphorus to zinc is ideal. If the ratio becomes higher than this (meaning there is more than 10 times more phosphorus than zinc in the soil) it is difficult for the plant to get enough zinc, and more needs to be added to the soil.

Manganese

Manganese plays a crucial role in photosynthesis, and is also important for nitrogen translocation and enzyme function in plants. It is involved in the production of lignin in plants, and sufficient amounts can help protect plants against attack by fungal disease. Manganese availability is closely tied to pH. If the soil pH is above 7.2, manganese availability decreases. A tissue test showing good levels of manganese in the plant on a high pH soil – this is a good indicator that the soil has healthy biological activity.

Copper

Copper is involved in the immune system of plants. It is important for proper enzyme function, and can help control moulds and fungus. It also increases stalk strength and helps produce a higher quality crop with greater storability. Recommended copper levels are over 5 ppm. It is important to note, before adding any copper into the soil, that a lot of organic fungicides are copper based.

Iron

Nitrogen-fixing bacteria in the soil require iron. It is also important for chlorophyll production and energy release in cells. Adequate amounts of iron in the soil are necessary, but if levels get too high it can tie up phosphorus. This becomes a problem if iron levels are higher than unavailable phosphorus levels in a soil test. If iron is deficient (below 20 ppm), there is a potential for chlorosis and decreased photosynthesis in plants.

Carbon inputs [13, 28]

Plants are composed of 40 – 45% of carbon. Some of the carbon and nutrients from dying plants are taken up by the next crop. Some of the plant tissue carbon is lost to the atmosphere as CO_2 when soil organisms consume it and respire, while some of the carbon stays in the soil where it can become stable organic matter. Amending soil with green manure crops, crop residues, manure and compost doesn't necessarily increase soil organic matter. Some carbon sources provide a quick flush of nutrients to the next crop, while others take longer to break down in the soil and instead build stable organic matter.

Characteristics of carbon inputs

GREEN CARBON

A carbon that breaks down quickly in the soil. The main function is to feed microorganisms, mainly bacteria, and provide a quick flush of nutrients to soil life and the next crop. It is primarily found in young living plants. Even some animal manures can be green carbon sources, such as pig and chicken manure, these types of manure are low in fibre. Manures that contain bedding, or manure from animals that have consumed a lot of forage would not be green carbon sources – most of these would be so called "brown carbon", hence most of the easily digested nutrients have been absorbed by the animal and what remains is a lower nutrient, high fibre material). Sugars can also be considered as a source of green carbon, because they feed soil bacteria, but do not provide nutrients like young plants or manures do.

Green carbon has a low carbon to nitrogen ratio (C/N). It is important to know, because it determines how the material breaks down in the soil. Since it is relatively high in nitrogen and low in lignin, soil organisms, primarily bacteria, digest green carbon quickly and release the nutrients from the green carbon source into the soil solution. Soil bacteria have a low C/N ratio in the own bodies, so as they die and other organisms consume them, nitrogen in a plant-available form is released into the soil. The rapid breakdown of green carbon in the soil results in a flush of available nutrients but very little build-up of organic matter. That is because some of the carbon from a green carbon source will be released back into the atmosphere as CO_2 when soil organisms consume the material and respire. Only a small fraction of this carbon will remain in the soil and over time be converted into the more stable black carbon or soil humus. It is also important to remember, if applying green carbon from manure or working in green cover crops, the nutrients from the green carbon source will quickly become available to the cash crop. Green carbon sources break down rapidly and go from green carbon source to soil bacteria and then to high nitrogen waste in a matter of a few days or weeks. It is totally possible to grow a nitrogen source by feeding soil bacteria a green carbon source. Even non nitrogen fixing crops such as young rye or oats can be a food source for soil bacteria including Azotobacter (the bacteria that turn atmospheric nitrogen into plant-available nitrogen in the soil). Feeding the soil bacteria will provide additional nitrogen and nutrients to the cash crop.

BROWN CARBON

A carbon source that is found in older, woodier plant materials, for example – corn stalks, residues from small grain crops, and mature cover crops such as one-metre-tall ryegrass. Brown carbon sources are basically materials with a high content of lignin or brown plant material including manures containing straw from bedding, or manure from animals that have consumed a lot of forage. Brown carbon has a high carbon to nitrogen ratio, which means it takes more time for soil organisms to digest it. Hence, soil organisms require nitrogen, and because brown carbon is relatively low in nitrogen, soil organisms must consume nitrogen from the soil as they digest brown carbon sources, resulting in a reduction in the available nitrogen in the soil.

Brown carbon is mainly consumed by soil fungi, which eat materials high in lignin and complex carbohydrates that are difficult for other organisms to break down. Fungi have a lower turnover rate than soil bacteria and therefore do not provide the same rapid influx of nutrients that bacteria and their food sources do – brown carbon doesn't provide a quick source of nutrients for growing crop. The main reason for brown carbon inputs – as soil organisms consume brown carbon, more of the carbon will remain in the soil to be converted into a stable form and eventually become humus.

Crop residue is also a brown carbon source, but it does not contribute to stable organic matter in the soil unless broken down. If residue is on top of the soil, it is not being digested. Despite the fact that residue on the soil look like soil organic matter, it is not doing anything to improve the soil, except for keeping a blanket on top to reduce erosion. Lying residue is oxidizing and much of the carbon in this residue is released into the atmosphere in the form of CO_2. If the residue is worked into the top layer of soil, it will come into contact with microorganisms that digest it. This begins the process of converting the carbon in the residue into stable organic matter in the soil. It can be recommended to work the residue into the soil in the spring, when the soil is warming up and the cover crop is growing and can capture the CO_2 released as microorganisms consume the residue and respire. This can also be provided by a sufficient blend of green and brown carbon sources. The green carbon provides some nitrogen helping to digest the brown carbon, so the nitrogen is not depleted from the soil as brown carbon residue is broken down.

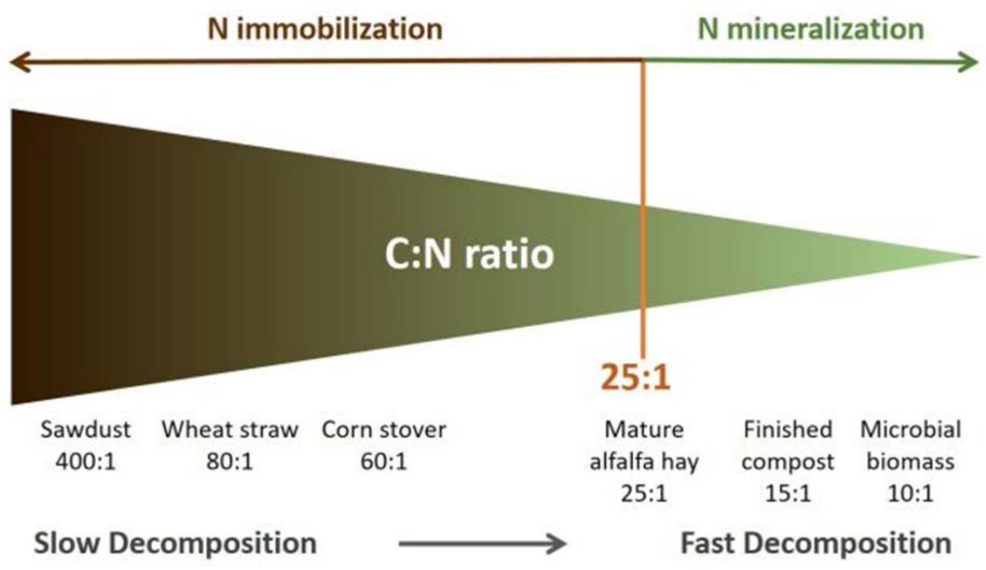
BLACK CARBON

A carbon source that is very stable and is formed over time as organic materials decay. It is the final product of decomposition in the soil. Black carbon is the rich black humus that provides soil with many of the beneficial properties of organic matter. Compost is partially composed of black carbon (there is a lot of variation in the amount, depending upon the type of materials that went into compost production, and the quality of compost also depends on the process of making it). The black, rich-smelling portion of well-digested compost is humus.

Unlike green carbon, black carbon doesn't provide a quick influx of nutrients to growing plants and unlike brown carbon, black carbon doesn't tie up any other soil nutrients after it is applied. Black carbon has a high CEC, meaning that applying sources of black carbon such as compost or mined humates helps to retain nutrients in a stable form that don't leach or tie up. Application of black carbon can also improve soil structure, soil water holding capacity (1% of humus increase will provide additional water holding capacity of 400 m^3per hectare) and provide many other benefits.

Managing soil carbon in a farming system means using a variety of different carbon sources and returning plant material to the soil at different stages of maturity. Adding both green carbon and brown carbon sources to soil each year is a good way to balance the need for crop nutrients with the need to maintain or build stable carbon in the soil.

Figure 2 - Relationship of decomposition speed and nitrogen fate to carbon: nitrogen ratios (C: N) of different residues (28)



C/N influences decomposition speed. The ratio also determines whether nitrogen will be mineralized (released) as the material is decomposed, or if nitrogen will be immobilized (tied up) by the decomposer community as they break down the material. The decomposition speed varies because decomposers (soil's microbiology) have different nutritional requirements and residues have differences in chemistry.

Tillage [1]

The basic reasons for tilling can be described as follows:

1. Soil aeration – In soils without the presence of oxygen, crop failure is guaranteed.
2. Soil water – The soil needs to absorb water when it rains and hold the water without pushing out all the air. Soil water also needs to be brought up to the roots when the soil dries out.
3. Crop residue or other organic matter – In order to allow residue or other organic matter to decompose and release the nutrients that these materials contain for the next crop, they need to be worked into the soil.
4. Soil fertility – Soils need a balance and mix of nutrients throughout the root zone. Water movement in the soil also provides nutrients. Proper tillage mixes and distributes nutrients throughout the soil.

Soil compaction [1, 13, 17, 18, 19]

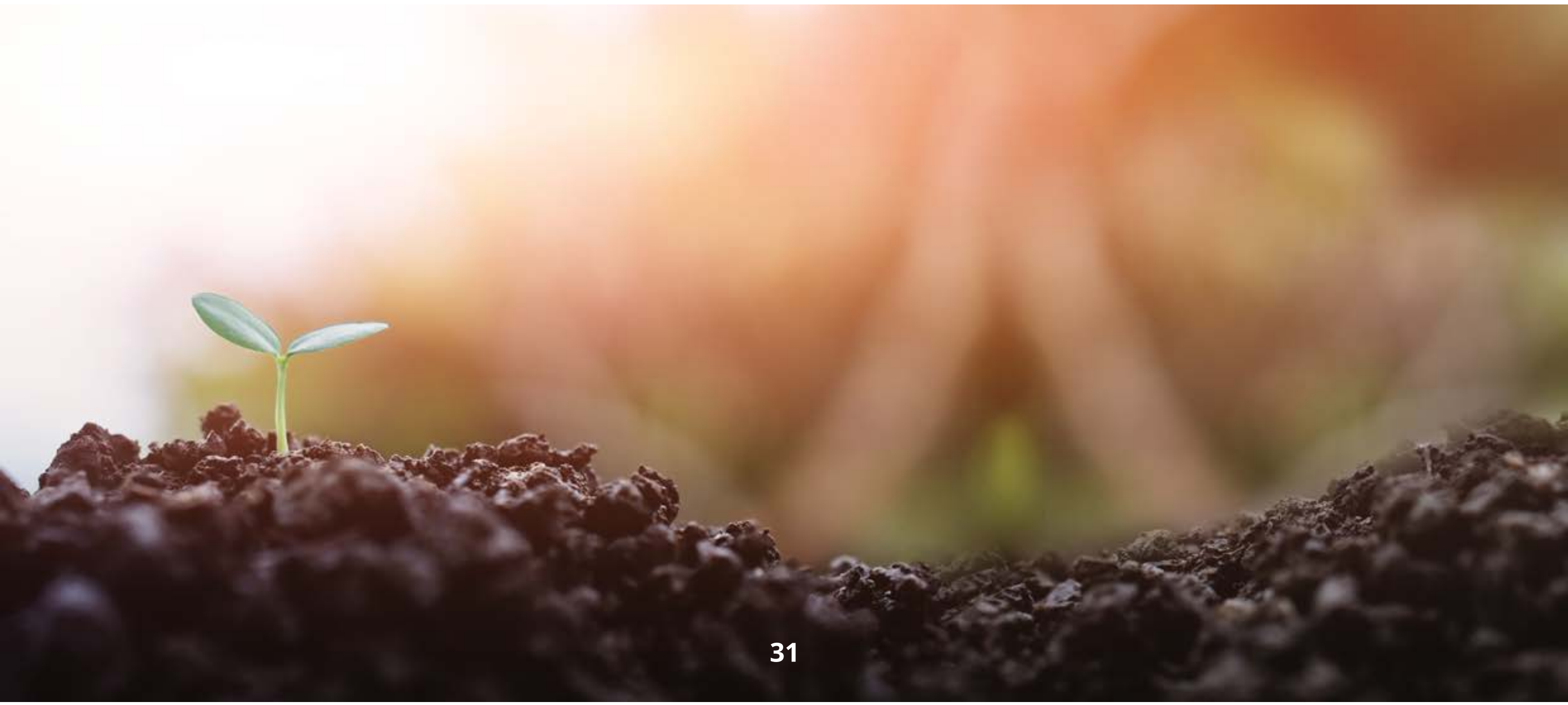
One of the main tillage problems is soil compaction. Soil compaction is caused by increasing soil density, along with decreasing porosity. Tiny soil particles move closer together, and there is less room for air and water to move through the soil. Soil aggregates break down, allowing tiny particles to become cemented together or to be held tightly together by electrostatic forces. Compaction can occur as surface crusting, as a hardpan in the upper layers or in the subsoil.

The main causes of soil compaction are the mechanical forces of tillage and driving on the wet soil. Driving on wet soil causes compaction in both topsoil and deeper layers, while most tillage equipment tends to cause a hardpan to form at deeper levels.
A further major cause of soil compaction is low organic matter content of the soil, especially low humus. This leads to crusting as well as compaction in the upper portion of soil (the plough layer). Humus and exudates produced by roots and soil microbes glue tiny particles together to form the larger aggregates which are necessary for good soil structure, aeration and root growth.

While some tillage is a good and necessary for soils to perform, more tillage doesn't bring more benefits. Aggressive tillage introduces a lot of air into the soil, when too much oxygen is introduced into the soil through tillage, there is a boost in the activity of microorganisms. They consume soil carbon, organic matter, and give off much of the that carbon in the form of CO_2 released into the atmosphere. If there are plants growing on the soil, they can catch some of this CO_2 via photosynthesis, carbon will be added back to the soil by incorporation of plant residue. If the soil is tilled when it is bare, for example in early spring before sowing, there are no plants that can capture the CO_2, which is lost to the atmosphere. This is very basic explanation why aggressive tillage results in the loss of soil carbon, apart from water or wind erosion of the bare soil.

Table 5 – Types of compaction and their remedies (17)

Compaction Type	Indications	Remedies/Prevention
Surface crusting	Breakdown of surface aggregates and sealing of surface Poor seedling emergence Accelerated runoff and erosion	Reduce tillage intensity. Leave residue on surface. Add organic matter. Grow cover crops.
Plough layer	Deep wheel tracks Prolonged saturation or standing water Poor root growth Hard to dig and resistant to penetrometer Cloddy after tillage	Plough with mouldboard or chisel plough, but reduce secondary tillage. Do primary tillage before winter (if no erosion danger exists). Use zone builders. Increase input of organic matter. Use cover crops or rotation crops that can break up compact soils. Use better load distribution. Use controlled traffic. Don't drive on soils that are wet. Improve soil drainage.
Subsoil	Roots cannot penetrate subsoil Resistant to penetrometer at greater depths	Don't drive on soils that are wet. Improve soil drainage. Till deeply with a subsoiler or zone builder. Use cover crops or rotation crops that penetrate compact subsoils. Use better load distribution. Use controlled traffic. Don't use wheels in open furrows.



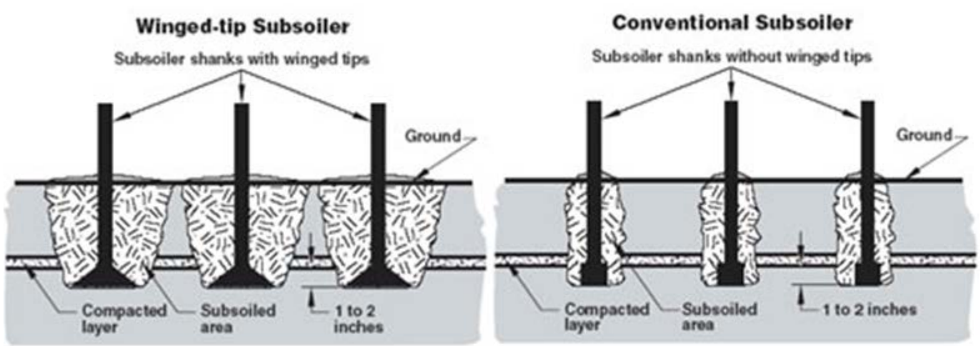
Tillage practices for organic farms [1, 13, 17, 18, 19, 23]

If the basics are implemented and mistakes avoided, such as tillage while the soil is wet, this can result in an overall reduction in tillage and therefore saving in costs. Tillage should be used when necessary, more tillage cannot solve problems primarily caused by tillage, such as breaking the hardpan with a subsoiler. However, if these practices are timed well and with the main purpose to improve the soil performance, the effect is maximized.

Subsoiling

Deep tillage to fracture a compaction layer. Sometimes there is also a lifting action to loosen deep soil for better water management and deep root growth. Subsoiling can be an effective technique to solve soil compaction problems.

Image 10 – Comparison of different subsoiler tips
Source: https://www.fs.fed.us/t-d/pubs/htmlpubs/htm08342828/page03.htm



However, if done at the wrong time or incorrect depth, it can cause more problems than it solves. Subsoiling a field with good soil structure has no point, it will only result in cutting the natural channels, making the matters worse. A good time for subsoiling is after harvesting, before or during the sowing of cover crops. Channels caused by subsoiler will help the cover crop to penetrate deeper into the soil and enhancing the effect. Another option is to subsoil with low-disturbance legs through growing cover crops to give them a new lease of life in poorly established areas. Subsoiling should not be performed without immediate cash crop or cover crop establishment to exploit the soil structure.

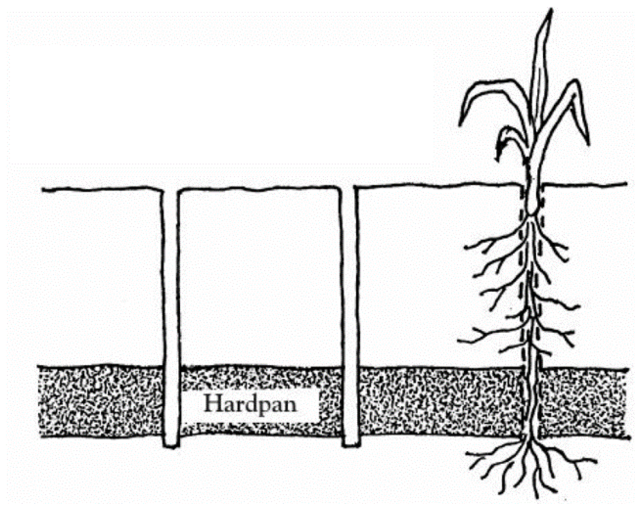


Image 11 – Roots can grow down slots below the hardpan after subsoiling (1)

Soils with a low calcium content that are high in silt or sand and low in organic matter will benefit the most. To relieve compaction, it is important to subtly lift the soil and stretch it – to create vertical cracks – this is where it is vital that the soil is dry enough to crack. If it is too wet it will be like plasticine and will not shatter. The vertical cracks are important so that the roots can bore into the soil, while the aerobic conditions assist biological activity to stabilize it further. Variable depth during each subsoiling should be applied as it can create a weakness, just like ploughing, when set to one depth over multiple years. It is recommended that the depth is varied, going shallower rather than deeper.

If there is a hard pan that needs to be broken up, the soil below the pan is often protected by this hardpan layer. This soil is usually in good condition, therefore working the subsoiler into this will take extra energy and may make things worse.

The most important aspect of a successful subsoiling is the working depth. When set properly, it is crucial to cause as little soil disturbance as possible. Subsoiler tips and shank shapes vary according to the manufacturer and the soil properties.

Image 12 – Subsoiler, and rock clearance system. Source: https://www.he-va.co.uk/he-va-products/cultivation/subsoiler/#gallery

Image 13 – Subsoiler equipped with an air seeder during cover crop establishment. Source: https://twitter.com/HEVA_uk/status/1172171859523231744/photo/1

Reduced ploughing (mould board plough)

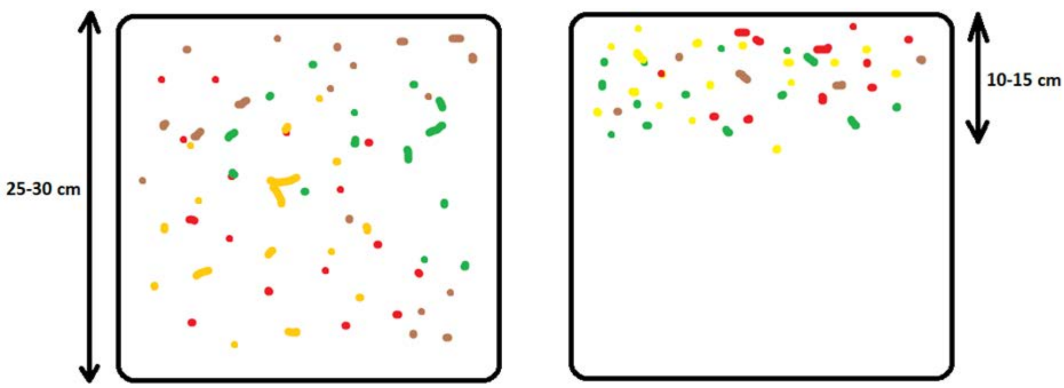
Ploughing is an incredibly effective form of tillage. It is used to turn large quantities of organic matter into the soil, including crop residue after harvesting, stubble, manure or cover crops. It is very effective in weed and pest suppression on an organic farm. Ploughing aerates the soil and mixes it effectively. Ploughs are very effective in breaking alfalfa leys in a single pass saving a lot of fuel for this operation.

However, if used improperly and extensively it may cause severe problems resulting in soil compaction or hard pan (plough pan) and neglecting all its benefits. Soil life forms such as earthworms are particularly sensitive to ploughing.

A mouldboard plough is used as a weed control tool by organic farmers, especially for perennial weeds such as thistle or couch grass. Yet, while very effective in perennial weed suppression, the main disadvantage in using a mouldboard plough as a weed control tool is the seed distribution throughout the whole working depth. Mouldboard ploughs are usually designed for a working depth of between 20 - 30 cm, depending on the soil type. Most weed seeds are activated by sunlight. When buried, they become dormant, but seeds stay active for many years and in some cases even decades! This phenomenon is called a soil weed seed bank. If there was a year with a lot of seeds, that were shattered from weeds or crops, they can be preserved in the soil weed seed bank for the future, creating a problem in following years. Operations such as seed bed preparation draw out those preserved seeds and expose the newly established crops to weed pressure. When the seeds are distributed at a shallower depth, it is easier to eliminate emerging weeds.

One of the causes of soil compaction is the passage of tractor wheels in the furrows. This can be eliminated by using a so-called on-land system that offsets the plough enough to either side for tractor wheels to stay completely on uncultivated land. Using a mouldboard plough for weed suppression surely eases the weed problem during that year, but potentially creates issues in following seasons.

Image 14 – Distribution of weed seeds in the soil depending on cultivation depth and practices.
Author: Adam Brezáni



There are many designs of mouldboard ploughs available on the market. The main problem with a mouldboard plough is its extensive use on a year-to-year basis. The whole depth of topsoil is turned, preventing the soil life from thriving. Not all mouldboard ploughs are so aggressive, and there are units available that work only a portion of the top soil. Even when shallow ploughing, it is not necessary to do it every single year, as it will cause a compaction layer just like a standard plough, since ploughing is a very aggressive operation towards soil life in any configuration. Reduced shallow ploughing should be used to turn in leys, high amounts of organic matter such as manure or compost ideally spread on the cover crop to make this operation most effective and reduce the risk of badly damaging the soil structure. When there is a lot of plant residue and amendments in the form of organic matter, the soil is less prone to compaction during the ploughing process.

Image 15 – An example of on-land ploughing system.
Source: https://www.kuhn.com/com_en/range/ploughing/mounted-reversible-ploughs/vari-master-l-on-land.html

Image 16 – Shallow mould-board plough.
Source: https://ien.kverneland.com/Ploughing-Equipment/Reversible-Mounted-Ploughs/Kverneland-Ecomat

Shallow incorporation of biomass

Ploughing can be an option for shallow incorporation of temporary grass and legume leys, using special shallow ploughs or adjusted standard ploughs. However, when there is a need to chop and incorporate larger volumes of biomass (like over-winter cover crop mixes) into the soil, a different approach has to be considered. Even though some ploughs can till the soil shallowly, the disturbance caused can be a limiting factor prior to establishing a crop. The soil is inverted and it takes some time to dry out, before equipment can enter the site or additional tillage is needed to prepare a seedbed. This will cause the soil profile to dry excessively and stress the following crop by soil capillary rise. Soil capillary rise can be eliminated by additional rolling, but this requires an additional pass of machinery, compacting the soil even more.

One of the options is to use a shallow passive disc implement, that will incorporate mulched crop residue 2 - 5 cm into the soil, creating a seed bed. This implement can be used for treating stubble and initializing seed shatter to germinate after harvest, while also able to sow cover crops. For optimal results, it is necessary to drive at a speed of between 15-20 km/h to ensure a thorough mix of soil and plant biomass and cover crop termination. The disc implement is not suitable for termination of alfalfa or grass/legume mixes.

Another device for shallow tillage that can terminate, incorporate alfalfa or grass/legume mixes and treat stubble is a tine cultivator with goosefoot-shaped tines. The cultivator can be set to variable depths depending on the soil conditions and needs of the operator. It undercuts the roots of the stand and brings the plants to the surface, where the sun desiccates them. Depending on the quality of stand, soil moisture and potential regrowth from plants, as their roots are still partially attached to the soil, a second pass may be required to terminate a ley. The downside of this tillage practice is its inability to work in larger volumes of plant biomass without previous mulching. The cultivator can be equipped with an air seeder to sow cover crops during the tillage process. The tines at the rear pull the sod on the surface where it dries quicker.

Image 17 – Passive disc implement for shallow cultivation of stubble or mulched biomass into the soil.
Photo: Martin Matěj

Image 18 – Tine cultivator with goose foot tips.
Sources: https://moderner-landwirt.de/schon-beim-drusch-an-die-stoppelbearbeitung-denken/ and https://www.mezger-landtechnik.de/portfolio-posts/treffler-tga300/

A rototiller can chop and incorporate large volumes of biomass in a single pass with adequate termination. This method requires more energy and is slower compared to previous ones as it is power-shaft driven. However, compaction is reduced, because there is no need to enter the site multiple times. A rototiller can cause a lot of damage to soil structure if used improperly and caution needs to be taken when using one. It is only recommended for use in situations with a large amount of plant biomass that is shallowly incorporated into the soil. Plant residue from cover crops protects the soil from being destroyed by the blades of the rototiller. Never use a rototiller on bare soil or when too wet. A rototiller can also be used to break temporary leys (alfalfa or grass/legume) in a single pass, when adjusted properly, since the blades are able to undercut the sod. It is recommended that you wait a few days after incorporation before establishing a cash crop, since microorganisms decomposing the residue might compete for water with the germinating seed.

Image 19 – Rototiller used to terminate cover crops and a detail at the blades' shape.
Source: https://www.falc.eu/en/prodotti/frese/fresa_bio_tiller.php#pdf

Roller crimping with direct drilling

A method of terminating cover crops without further incorporation. A cover crop of hardy winter species, which produce large volumes of biomass. A mixture of winter rye and hairy vetch is mostly used for roller crimper termination. It is a drum implement with a pattern of blades that knock the cover crop down and crimp it, ensuring the plants' veins are crimped, preventing the plant from regeneration. This creates a layer of dead mulch on top of the soil, which will protect the soil from overheating, erosion and hold water better. Another benefit is weed suppression. A cash crop is established directly into the dead mulch. This approach is mostly used for summer wide row crops such as corn, soy beans or sunflowers. It is necessary to cut through the thick mulch of residue, placing the seed directly into the soil, ensuring the best seed to soil contact. It is recommended that row cleaners are used in front of the seeder's coulters to prevent hair pinning.

For best results, rolling and drilling should be performed in a single pass by attaching the crimper on the tractor's front hinge. The recommended blade pattern for a roller crimper is a so-called chevron pattern ensuring the best possible cover crop termination.

Plans for building a roller crimper, can be found at https://rodaleinstitute.org/education/resources/roller-crimper-blueprints/. The timing of crimping is crucial for preventing the cover crop from regenerating. The best time for termination is after flowering, when the crimped cover crop doesn't have enough energy for regrowth. Cover crop biomass should be at a sufficient level to create a thick mulch, otherwise the field will be prone to weeds before the full canopy closure of the cash crop, especially in uncovered spots. Insufficient termination of cover crop will result in its regrowth and competition with the cash crop. It is nearly impossible to get a regenerated cover crop under control.

Image 20 – Roller crimping and drilling cash crop in a single pass.
Source: https://croproller.com/crop-roller-benefits/

Image 21 – Row cleaner for no-till coulters.
Source: https://www.yetterco.com/products/27-plantermount-row-cleaner-combos/303-2967035-row-cleaner-for-notill-coulters

Image 22 – Roller crimper with a chevron pattern.
Source: https://rodaleinstitute.org/why-organic/organic-farming-practices/organic-no-till/

Cultivation on an organic farm [1, 13, 19]

Prevention methods

It is cost effective to focus on preventing the weed problem rather than trying to solve the weed problem. Such methods are:

- Mowing down or mulching areas that are excessively infested by weeds beyond recovery.
- Prohibiting weeds going to seed, which could increase the soil weed seed bank.
- Avoiding seed shattering during harvest.
- Using practices to promote the weed seed germination by shallow tillage rather than burying the seed in the soil by incorporation. Germinated weeds can be eliminated with an extra pass of shallow tillage.
- Using cover crop leys such as alfalfa or a mixture of legumes and grasses for a year or two in crop rotation to suppress the weeds.
- Keeping the soil properties in balance – chemical, physical, biological.
- Using vigorous crop varieties that will result in rapid canopy closure, suppressing the weeds.
- Undersowing and intercropping companion crops along with the cash crop.

Mechanical cultivation

Since the use of synthetic pesticide is prohibited in the organic system, other alternatives have to be utilized. Practices such as mechanical cultivation, using various implements, or a prevention plans need to be applied.

1.Rotary hoes and tine cultivators (harrows and weeders) – both can be used for pre-emergence and post-emergence weed control. Pre-emergence cultivation is done three to five days after the crop has been planted/sown for corn or soybeans. Post-emergence cultivation is an important tool to eliminate weeds that emerge around the same time as the crop. Among the weeds that emerge after planting/sowing, these will be the ones that affect crop yield the most. Broadcast or blind cultivation can be performed after the crop has emerged. However, there are several factors to consider such as the type of crop and crop maturity. This type of cultivation has the greatest risk for crop damage and planting rates may need to be increased to compensate for this type of field operation. The best-case scenario for post-emergence cultivation is when the crop is larger than the weeds, which results in the crop being more strongly/deeply rooted and able to withstand the cultivation, and the weeds are smaller and more easily uprooted.

Table 6 – Optimum timings for post-emergence harrowing for weed control. Source: https://www.dal.ca/faculty/agriculture/oacc/en-home/resources/pest-management/weed-management/organic-weed-mgmt-resources/weeds-post-emergence.html

Crop	Stage for harrowing
Wheat	2-4 leaf
Barley	2-4 leaf, before tillering
Oat	Not recommended
Sunflower	Up to 6 leaf
Fababean	5-15 cm tall
Lentil	Seedling less than 10 cm tall
Field pea	Seedling less than 10 cm tall
Canola	Not recommended
Flax	Not recommended

Post-emergence broadcast cultivation is performed with rotary hoes and harrows. The best time to rotary hoe is when weeds are newly germinated and have reached the "white thread" stage (also called the "white root" or "white sprout" stage). Weeds in the white thread stage have not emerged from the soil. The top 2 centimeters of soil must be examined to determine if weeds are at the white thread stage. Grass weeds that are past the one-leaf stage or broadleaf weeds that have formed their first true leaves are too firmly-rooted to be controlled with the rotary hoe. However, harrows and tine weeders are more effective than the rotary hoe on weeds that are somewhat more mature. Rotary hoes and tine harrows are more effective on warm, sunny, and windy days, which help dry out small weed seedlings pulled out of the soil by these operations - desiccation.

Soil type and condition may determine which tool is best for post-emergence cultivation. Rotary hoes are more effective on crusted soils than are harrows or tine weeders. Rotary hoeing is less effective when the soil surface is rough. Tine weeders, harrows and rotary hoes are all hindered by large amounts (greater than 30% coverage) of surface residue. Harrows and tine weeders may be more effective on loamy soils than are rotary hoes. Tine weeders have different tines varying in flexibility and thickness that can be used depending on the heaviness of the soil. Rotary hoes are operated at speeds of 12-20 km/h, while harrows are usually operated at speeds between 7-10 km/h. A tine harrow will not work properly with a lot of residue on the soil surface. Both can be equipped with seeders for establishing companion crops.

Image 23 – Rotary hoe equipped with an air seeder.
Source: https://www.hatzenbichler.com/en/rotary-hoe

Image 24 – Tine harrow equipped with an air seeder.
Source: https://www.hatzenbichler.com/en/original-harrow

2. Inter-row cultivation - a method of cultivation to control weeds that grow between the rows. Row cultivation is secondary to weed control operations performed earlier, because the earlier emerging weeds are more critical to control due to their greater potential to reduce crop yield. Inter-row cultivation is low risk to the crop compared to post-emergence broadcast operations. The cultivation is performed between the rows, the crop should not be directly affected by the machinery. Cultivation is performed, when the crop is at least 10 cm tall and up to a height where equipment will still clear the crop. Timing of inter-row cultivation is not as critical an issue as it is for broadcast cultivation. Cultivators can affect weeds up to 12 – 15 cm tall as compared to a rotary hoe which only controls newly germinated weeds. Generally, cultivation is performed at depths less than 5 cm to prevent the roots from being too damaged and soil moisture conserved. The goal is to maximize the cultivation area between the crop rows without damaging the crop. Try not to rely on inter-row cultivation as the primary method for weed control – use in conjunction with pre- and post-emergence operations. Inter-row hoes are mainly used in this type of cultivation.

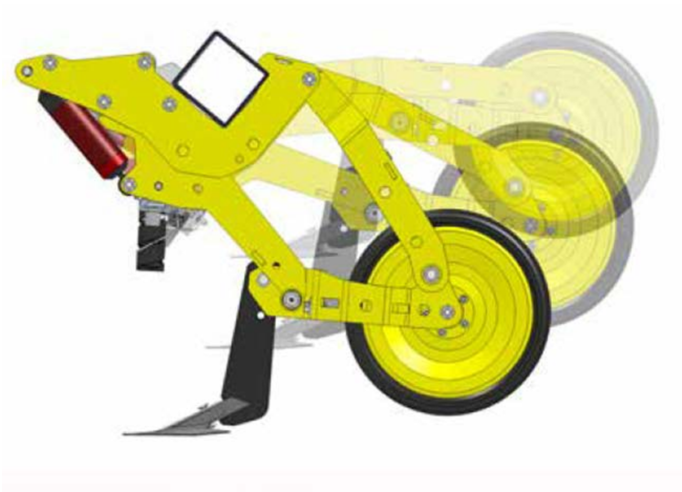
Equipment for wide row crops is more available on the market. However, technologies for the use of inter-row hoeing exist for cereal production as well. The most important aspect is to increase the row width from the standard 12,5 - 15 cm to at least 25 cm or wider, if band sowing is performed even wider rows are required. The last pass of cultivation can be a good opportunity to establish a companion crop or a ley in a current stand. Cultivators can be equipped with a camera steering assistant for more accurate and convenient work. Particularly for wide row crops it is recommended that the cultivator is equipped with plant protectors.

Image 25 – Interrow cultivation of cereals.
Source: https://www.hatzenbichler.com/en/weed-interrow-cultivator

Image 26 – Interrow cultivator for wide row crops - corn, sunflowers, soybeans, etc. The cultivator is equipped with an air seeder and plant protectors.
Source: https://www.hatzenbichler.com/en/corn-interrow-cultivator

Image 27 – System Cameleon - a drill and interrow hoe in one machine. Each hoe is attached to a parallelogram to cope with terrain. It is equipped with a camera steering assistant and capable of undersowing cover crops during hoeing.
Source: https://www.pargasgard.fi/fi/system-cameleon

Image 28 – Parallelogram design of System Cameleon.
Source: https://www.gothiaredskap.se/index.php/en/system-cameleon-en/functions/weed-control



There is a rising trend of growing cereals in wide rows (25 and 37,5 cm or other widths depending on the machinery) or band sowing. This enables weed control methods to be integrated, such as interrow hoeing. However, there are also qualitative benefits to this method as well. Especially in winter wheat, wide row cultivation can bring some benefits such as: more grains per spike, higher grain weight and higher crude protein levels, resulting in higher quality and a higher retail price of the product. These results could be obtained without significant yield reduction. Such results are due to the fact that the stand structure of wider rows allows more light to enter the stand compared to the narrow row spacing. A crop has more active photosynthesis area for a longer time, since the lower leaves do not die as rapidly as they would in a denser stand. Longer photosynthesis results in more protein being accumulated in the grain.

3.Weed control based on physiological differences between weeds and cash crops – a passive implement that is used to selectively comb and cut off weeds beyond the recovery point.

Basic principles:

1. The crop is thinner than the weeds;
2. The weeds are higher than the crop;
3. There are differences in stiffness between crops and weeds.

Image 29 – Combcut® during mowing weed.
Source: https://www.primewest.co.uk/combcut/

For effective weed elimination, timing is crucial. The optimal time for mowing weeds tends to be during stem elongation. Optimal working speed is 10 – 15 km/h. This weed control method can be used in cereals, legumes, leys/grassland, corn, potatoes, root vegetables. Selective weed control helps to lower the weed seed bank of the soil.

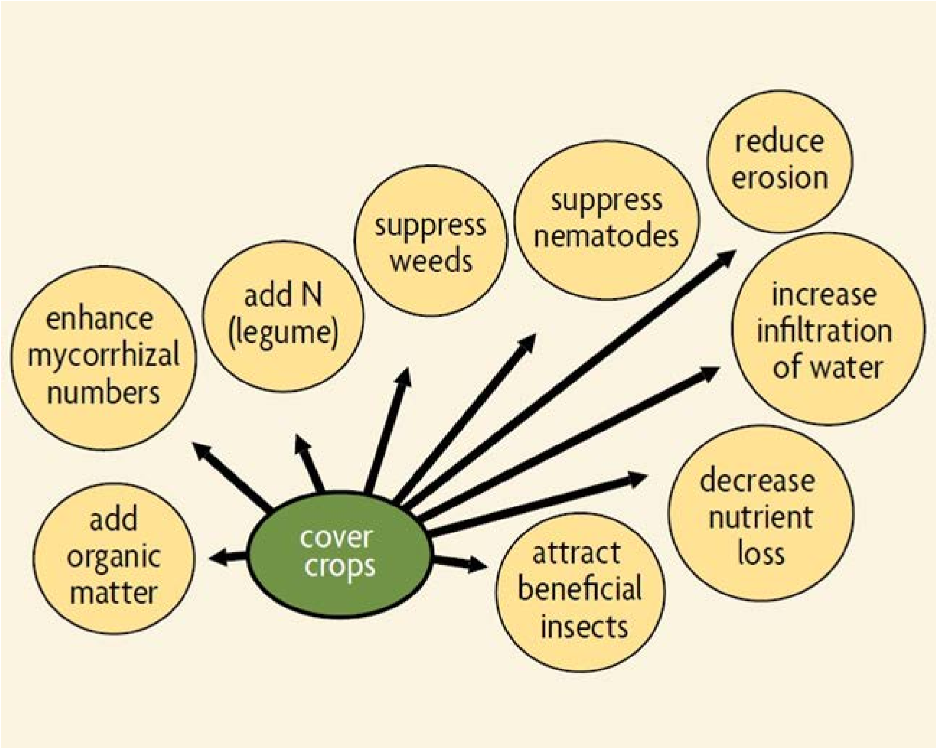
4. Weed control based on cutting extended weeds – a shaft driven implement that cuts off the tips of weeds that stick out above the stand of the cash crop. Cutting the tips of the weeds will prevent them from maturing and infesting the site. This implement is effective on black grass and wild oats.

Image 30 – Weed Surfer™ cutting the tips of weeds.
Source: https://www.ctmrootcropsystems.co.uk/products/weed-surfer/

Cover crops [13, 17, 20, 21, 26]

Cover crops help to create maximum plant diversity. Green plants feed soil life, build organic matter, and capture nutrients in their tissue. Keeping nutrients in a biological cycle means these nutrients will not leach or erode, and they are in a form that is linked to biology, so it is easier for plants to access them. Nutrients held in a cover crop do not show up on a soil test, but as they break down, nutrients released into the soil are in plant-available form.

Figure 3 – Cover crops provide multiple benefits (17)



Cover crops enhance overall soil fertility:

Chemical fertility

Nitrogen fixation and restoration, macronutrient and micronutrient restoration and availability are the benefits of a cash crop, while improving soil fertility. Nutrients taken up and fixed by cover crops are then slowly released. Despite the fact that cover crops tend to lower the yield during the first years, their introduction to the system brings long term sustainability to production. Usage of cover crops will prevent nitrogen hunger in the soil for the following cash crop via improved soil biology. Soil bacteria will nourish the cash crop, as cover crops feed the soil life via photosynthesis. It is important to note that usage of cover crops enhances only nitrogen and carbon respectively. Other nutrients need to be added to the soil, using external amendments.

The relationship between carbon and nitrogen in cover crops: The C/N ratio determines how fast the biomass will break down in the soil. When the C/N ratio of a cover crop is wider than the C/N ratio of microorganisms, the microorganisms will consume nitrogen from the soil environment to level their own C/N ratios. The C/N ratio increases with the age of the cover crop. A developed stand has woodier tissue, while a younger stand is nitrogen rich and contains less carbon. Green mustard will break down faster, but mustard past bloom will stay in the soil for a longer time. Soil usual C/N ratio is 10:1. Each biomass, where the C/N is wider than 30:1, will digest nitrogen for its breakdown and biomass with a C/N ratio between 10 and 25:1 will release nitrogen. In the case of later stand termination, a large proportion of nitrogen can be digested by microorganisms, making nitrogen scarce for the following cash crop. To prevent this, it is important to choose cover crops with a narrower C/N ratio or terminate the stand in the optimal stage.

Physical fertility

The implementation of correct practices (cover crops, tight and diverse crop rotation, correct tillage practices, etc.) will increase the soil organic matter, quality and depth of structural organization of the soil, improving water storage and management. Better utilization of cover crops in the system will increase the autonomy of cash crops by better stress resilience and overall health potential. Healthy soil can reduce the need for tillage and external inputs to the minimum. The need for irrigation is also lower.

Biological fertility

Development of intensive and diverse biological activity helps to maintain the ecological balance, where pests are mostly controlled by their predators. Intensive and diverse soil life is a guarantee of appropriate nutrient supply to cash crops. Plants use nutrients from the soil solution only partially. In reality, plants are nourished by a great quantity of soil microorganisms in the rhizosphere, exchanging energy from the root exudates. Cover crop management is one of the fundamental pillars of effective agricultural methods that are considerate to the environment. Soil life has become one of the limiting factors of current agriculture systems. The introduction of cover crops, reduced tillage systems and phytosanitary approaches can sustain sufficient production in following years.

Prior to cover crop selection, several things need to be considered. Soil conditions, climate and the purpose of the cover crop:

- Is the main purpose to add available nitrogen to the soil, or to scavenge nutrients and prevent loss from the system? (Legumes add nitrogen; other cover crops take up available soil nitrogen.)
- To provide large amounts of organic residue?
- Is the cover crop intended as a surface mulch, or to be incorporated into the soil?
- Is erosion control in the late fall and early spring a primary objective?
- Is the soil very acidic and infertile, with low availability of nutrients?
- Does the soil have a compaction problem (Some species, such as sudan grass, sweet clover, and forage radish are especially good for alleviating compaction)?
- Is weed suppression the main goal (Some species establish rapidly and vigorously, while some also chemically inhibit seed germination of weeds)?
- Which species are best for a specific climate (Some species are more winter-hardy than others)?
- Will the climate and water-retention properties of the soil cause a cover crop to use so much water that it harms the following crop?
- Are root diseases or plant-parasitic nematodes problems that need to be addressed? (Winter rye, for example, has been found to suppress a number of nematodes in various cropping systems)? *

In most cases, there are multiple objectives and multiple options for cover crops.

Types of cover crop

Legumes

Leguminous crops are often very good cover crops. Summer annual legumes, usually grown only during the summer, include soybeans, peas, and beans. Winter annual legumes, which are normally drilled in the fall and counted on to overwinter, include Austrian winter field peas, crimson clover, hairy vetch, and subterranean clover. Some, like crimson clover and field peas, can overwinter only in regions with mild frost. Hairy vetch is able to withstand fairly severe winter weather. Biennials and perennials include red clover, white clover, sweet clover, and alfalfa. Crops usually used as winter annuals can sometimes be grown as summer annuals in cold, short-season regions. Also, summer annuals that are easily damaged by frost, such as cowpeas, can be grown as a winter annual. One of the main reasons for selecting legumes as cover crops is their ability to fix nitrogen from the atmosphere and add it to the soil. Legumes that produce a substantial amount of growth, such as hairy vetch and crimson clover, may supply over 100 kg/ha of nitrogen to the next crop.

**More information about usage of proper crop rotation and database of soil-borne diseases and nematodes can be found at https://www.best4soil.eu/*

Legumes such as field peas, big flower vetch, and red clover usually supply 30 to 80 kg/ha of available nitrogen. Legumes also provide other benefits, such as attracting beneficial insects, helping to control erosion, and adding organic matter to the soil.

Grasses

Commonly used grass cover crops include the annual cereals (rye, wheat, barley, oats), annual or perennial forage grasses such as ryegrass, and warm-season grasses such as sorghum or Sudan grass. Non-legume cover crops, which are mainly grass species, are very useful for scavenging nutrients, especially nitrogen left over from a previous crop. They tend to have extensive root systems, and some establish rapidly and can greatly reduce erosion and soil compaction. In addition, they can produce large amounts of residue and, therefore, can help add organic matter to the soil. They can also help suppress weed germination and growth. A problem common to all grasses is that if the crop is grown to maturity for the maximum amount of residue, the amount of available nitrogen for the next crop is reduced. This is because of the high C:N ratio, or low percentage of nitrogen, in grasses near maturity. The problem can be avoided by killing the grass early or by adding extra nitrogen in the form of manure or compost. Another way to help with this problem is to supply extra nitrogen by seeding a legume-grass mix.

Brassicas

Brassicas used as cover crops include mustard, canola, and forage radish. They are increasingly used as winter or rotational cover crops in vegetable and specialty crop production, such as potatoes and tree fruits. Canola grows well under the moist and cool conditions of late fall, when other kinds of plants are going dormant for winter. Forage radish has attracted a lot of interest because of its fast growth in late summer and fall, which allows significant uptake of nutrients. It develops a large taproot, 2,5 - 5 cm in diameter and 30 cm or more long, that can break through compacted layers, allowing deeper rooting by the next crop. Forage radish is winterkilled and will decompose by spring, but it leaves the soil in friable condition and improves rainfall infiltration and storage. It also eases root penetration and development by the following crop. Canola and other brassica crops may function as biofumigants, suppressing soil pests, especially root pathogens and plant-parasitic nematodes. Any expectations that brassicas automatically eliminate pest problems need to be taken with a pinch of salt. They are a good tool and an excellent rotation crop, but pest management results are inconsistent. More research is needed to further clarify the variables affecting the release and toxicity of the chemical compounds involved. Because members of this family do not develop mycorrhizal fungi associations, they will not promote mycorrhizae in the following crop.

Buckwheat

Buckwheat is a summer annual that is easily killed by frost. It will grow better than many other cover crops on low-fertility soils. It also grows rapidly and completes its life cycle quickly, taking around six weeks from planting into a warm soil until the early flowering stage. Buckwheat can grow more than 60 cm tall in the month following sowing. It competes well with weeds because it grows so fast and, therefore, is used to suppress weeds following an early spring vegetable crop. It has also been reported to suppress important root pathogens, including *Thielaviopsis* and *Rhizoctonia species*. It is possible to grow more than one crop of buckwheat per year in many regions. Its seeds do not disperse widely, but it can reseed itself and become a weed. Mow or till it before seeds develop to prevent reseeding. It has an acidic root, draws a lot of phosphorus out of the soil especially from soil reserves, and produces a lot of biomass. In addition, buckwheat has a shallow dense root system that pulls in a lot of minerals and holds them until the buckwheat plant breaks down and releases those minerals back into the soil in a plant-available form.

Besides being an excellent cover crop, buckwheat is a perspective cash crop as well. It is not frost hardy, so it needs to be established later in the season depending on the area. It can be used as a relay crop, meaning it gives a second harvest of grain in the season after early crops such as crimson clover or early cereals. Care must be taken during post-harvest handling, since buckwheat contains a lot of green biomass when harvested. It should be aerated and dried as soon as possible to avoid grain rotting and mould infestation.

Table 7 – Multi-purpose cover crops (24)

Purpose	Species
Maximum biomass production	Sorghum or Sudangrass, Niger seed, Crotalaria (sun hemp), Pearl Millet, Black oats
Nitrogen fixation	Faba beans, Field peas / Austrian winter peas, Chickling vetch, Hairy vetch / Common vetch, Lupines, Lablab beans / Cowpeas
Breaking soil compaction	Tillage radish (Daikon radish), Oilseed radish, Mustard, Phacelia, Flax

Establishing cover crops

If the main goal is to accumulate a lot of organic matter, it is best to grow a cover crop for the whole growing season, which means no cash crop will be grown that year. Alfalfa or legume-grass mixes can serve this purpose. One-year leys are effective in perennial weed suppression and useful with very infertile or eroded soils. It also helps the production systems when no manure is available.

Sowing after cash crop harvest

Most cover crops are established after the harvest of a cash crop. In this case, there is no competition between the cover crop and the main crop. The seeds can be direct drilled into the stubble or sown during ultra-shallow cultivation that initializes the germination of weed and shattered seeds along with the sown cover crop seed. Winter rye is the most reliable cover crop for most conditions, and also has a phytosanitary effect through the production of exudates, which are allelopathic to many common weeds.

Interseeding/undersowing

This involves the interseeding/undersowing of cover crops during the growth of the cash crop. Cover crops are commonly undersown in winter grain crop systems or frost seed-sown in early spring.

Frost seeding is the practice of broadcasting red clover into winter wheat just prior to green-up. In most years, the ideal time is between mid-March and early-April. It is important to have snowmelt prior to frost seeding. Deep snow will result in the seed being carried to lower areas of fields as the snow melts and can result in poor stands. Seasonal freeze-thaw cycles cause the soil to repeatedly develop small cracks on the surface, allowing the clover seed to achieve good soil contact for germination. Seed inoculation is highly recommended in fields where red clover has not been grown within the past few years.

Delaying sowing the cover crop until the cash crop is off to a good start means that the commercial crop will be able to grow well despite the competition. Well-established cover crops require moisture and, for small-seeded crops, some covering of the seed by soil or crop residue. It is important not to bury small seed too deeply, therefore a separate seeder is recommended during sowing, which will drop the seeds on the soil surface before tines gently work them 1-2 cm into the soil. Seed broadcasting during or after the last cultivation of wide row crops is also an option. If a row cultivator with an air seeder is available, this is the best establishment method.

Small-grain cover crops that are broadcast during interseeding or underseeding serve as an erosion protection for the cash crop. Wide row crops are particularly prone to water and winter erosion. Cover crops in corn can serve as a protective layer/mat for the soil during harvest. Corn is usually harvested later in the season, when the soil is wet and prone to compaction by heavy equipment, and cover crops can protect the soil from being compacted.

Despite the fact that cereals are grown at higher rates, they do not provide sufficient soil protection against water erosion, and interseeding or undersowing is recommended. Another benefit of interseeded and undersown cover crops is the ability to nourish the soil biology after the cash crop has flowered (especially cereals). In this stage the cash crop transfers most of its energy into grain production, limiting the sugar flow to the roots. The roots cease the production of root exudates, which usually feed the soil microorganisms. Cover crops can subsidize the cash crop and nourish soil biology to maintain high activity. Grasses are exceptionally good at this, but clovers can provide more nitrogen to the soil.

Image 31 – Alfalfa emerging through oat stubble.
Photo: Adam Brezáni

<u>Intercrops and living mulches</u>
Intercropping has many benefits. Compared with bare soil, ground cover provides erosion control, better conditions for using heavy machinery during harvesting, higher water-infiltration capacity, and an increase in soil organic matter. In addition, if the cover crop is a legume, a significant build-up of nitrogen may be available to future cash crops. Another advantage is the attraction of beneficial insects, such as predatory mites, to flowering plants. Less insect damage has been noted under polyculture than under monoculture.

Growing other plants near the cash crop also poses potential dangers. The intercrop may harbour insect pests. Most management decisions relating to the use of intercrops are connected with minimizing competition with the cash crop. If an intercrop grows too tall, it can compete with the cash crop for light, or may physically interfere with the main crop's growth or harvest. Intercrops may compete for water and nutrients.

The use of intercrops is not recommended when rainfall is barely adequate for the cash crop in the region. One way of reducing competition is to delay sowing intercrops until the main crop is well established. Soil-improving intercrops established by delayed planting into annual main crops are usually referred to as cover crops. Another way to reduce competition from the cover crop is to plant the cash crop in a relatively wide cover-free strip. This provides more distance between the main crop and the intercrop rows.

In-situ and ex-situ cover crop mulch

Cover crops can be used for mulch production in potato or vegetable production.

1. In-situ mulch – grown on the same plot as potatoes or vegetables. Cover crops are sown on the bed in autumn (usually winter rye mixed with hairy vetch or peas) creating a thick stand that is terminated prior to potato planting or vegetable transplantation. Termination can be conducted with a roller crimper or a flail mower after the flowering of cereals and the bloom stage of legumes. A special transplanter has to be used for planting potatoes or vegetables. If some of the terminated biomass regenerates, a lifted flail mower can be used to mow down such plants, just above emerging potatoes or vegetables.
2. Ex-situ mulch – grown on a different plot than potatoes or vegetables. Cover crop, sown in autumn (usually winter rye mixed with hairy vetch or peas) chopped into 5 – 10 cm long pieces, which are transported to the production plot. The mulch is spread by means of a manure spreader with horizontal beats to ensure an even spread of mulch on prepared beds – a covering mat thickness of around 8 cm is optimal. The mulch is spread prior to vegetable transplantation. In the case of potatoes, mulch can be spread either prior to planting or when the potato plants have emerged.

In both mulch applications, it was found that potatoes are less susceptible to potato beetle infestation and more resistant against phytophthora infections. Vegetables grown under such conditions have a prolonged storage life. Mulch provides evaporation protection, feeds earthworms which pull the plant residue into the soil and digest it while aerating the soil. In the case of ex-situ vegetable production, when vegetables are transplanted directly into the mulch mat, it can provide some nutrient nourishment to the vegetable crop as well. The portion of cereals and legumes in a mix has to be balanced, adding more legumes means that the mulch won’t last as long on the soil surface (faster breakdown) as it would when more cereals are grown. This depends on specific needs and growing conditions.

Image 32 – A winter mix of winter rye, hairy vetch and crimson clover prior to termination. Photo: Martin Matěj

Image 33 – Spreading cover crop mulch over emerged potatoes. Source: https://humus-macht-leben.com/bodenfruchtbarkeit/kartoffel-mulchen/

Image 34 – MulchTec, a solution for vegetable transplantation into high cover crop residue with a PTO driven slicing mechanism. The transplanter is also equipped for application of organic zone fertilizer. Source: https://mulch-gemuesebau.de/wp-content/uploads/mulchtec-flyer-english.pdf

Crop rotation [1, 13, 17, 22, 25]

It is well known that monoculture, where the same crop is grown year after year, brings with it certain weed species. It can relate to tillage or fertilization, but another factor is the degraded, low-humus soil from continuous row crops like corn, cotton or soybeans. Usually, as the years go by, higher rates of fertilizer are needed, along with pesticides and more herbicides. Many scientific studies have proved that when crops are rotated, not only does yield improve (with less outside fertilizer being required), but soil structure improves and weed populations (species) change. Each type of weed grows best under certain soil conditions and nutrient balance. Obviously, it is necessary to plan a sensible crop rotation that works for the farm (for the soil, climate and pocketbook) and one that eventually builds up and improves the soil so that adverse soil conditions can be eliminated. Alternation of soil-building crops (legumes, fine-rooted grasses) with soil-depleting crops (corn) is required. Growing nitrogen-fixing legumes just before high-nitrogen consuming crops like corn means less purchased nitrogen source is needed. This can also be viable for winter wheat or spelt, where legume leys such as alfalfa can increase crude protein levels in grain. Hay crops are excellent soil builders. Even if the farm has no livestock, hay can be grown as a cash crop, or grass/legume cover crops can be sown in the fall between grain crops. A short or "tight" rotation works better than leaving a field in the same crop for more than a year or two (or three for hay). The idea is to keep the weeds "off balance" and to have a different crop just about every year (or two). Also, some crops may suppress weed growth by shading or by allelopathic effects. Common allelopathic crops include rye, barley, oats, wheat, corn, tall fescue, sorghum, Sudan grass, soybean, alfalfa, red clover, pea, field bean, sunflower and buckwheat.

General Principles to Guide Crop Rotation

Adapted from Building Soils for Better Crops (2009) (17)

1. Follow a legume crop with a high-nitrogen-demanding crop.
2. Grow less-nitrogen-demanding crops in the second or third year after a legume crop.
3. Grow annual crops for only one year in a particular location.
4. Don’t follow one crop with another closely related species.
5. Use crop sequences that promote healthier crops.
6. Use crop sequences that aid in controlling weeds.
7. Use longer periods of perennial crops on sloping land.
8. Try to grow a deep-rooted crop as part of the rotation.
9. Grow some crops that will leave a significant amount of residue.
10. When growing a wide mix of crops, try grouping into blocks according to plant family, timing of crops, (all early season crops together, for example), type of crop (root vs. fruit vs. leaf), nutrient needs, or crops with similar cultural practices.

Crop Rotation Planning Steps

The following steps are adapted from Crop Rotations on Organic Farms (2020)

1. Identify and prioritize your goals for the crop rotation (e.g., organic compliance, weed control, disease control, soil quality).
2. List desired crop mix.
3. Check for excessive acreage in one family.
4. Identify crop couplets and short sequences that work on the farm (including cover crops).
5. Make a crop-rotation planning map, noting which beds or fields (or parts of fields) are problem areas that might affect certain crops.

It is important to keep in mind that the ideal plan is flexible enough to respond to changing economic and weather conditions while at the same time maintaining the health of your soil and the economic health of your farm. Diversified operations growing many different kinds of crops should focus on good crop sequencing, which requires accurate records of crops grown in each bed or field.

Crop list English to Latin

Alfalfa – *Medicago sativa*
Austrian winter field peas – *Pisum sativum L.*
Barley – *Hordeum vulgare*
Black oat – *Avena strigosa Schreb.*
Canola – *Brassica napus*
Chickling vetch – *Lathyrus sativus*
Common vetch – *Vicia sativa*
Corn – *Zea mays subsp. Mays*
Cotton – *Gossypium hirsutum*
Cowpeas – *Vigna unguiculata L. Walp.*
Crimson clover – *Trifolium incarnatum*
Faba beans – *Vicia faba L.*
Field pea – *Pisum arvense L.*
Flax – *Linum usitatissimum*
Forage radish/oilseed radish – *Raphanus sativus*
Hairy vetch – *Vicia villosa*
Italian Rye Grass – *Lam. Festuca perennis*
Lablab beans – *Lablab purpureus (L.) Sweet*
Lentil – *Lens esculenta*
Lupins – *Lupinus albus L.*
Mustard – *Brassica nigra*
Niger seed – *Guizotia abyssinica*
Oats - *Avena sativa L.*
Pearl miller – *Pennisetum glaucum*
Potatoes – *Solanum tuberosum*
Red clover – *Trifolium pratense L.*
Sorghum – *Sorghum bicolor*
Soybean – *Glycine hispida (Moench) Maxim.*
Subterranean clover – *Trifolium subterraneum*
Sudan grass – *Sorghum sudanense*
Sunflower – *Helianthus annuus*
Sunn hemp – *Crotalaria juncea*
Sweet clover – *Melilotus officinalis (L.) Lam.*
Tall fescue – *Festuca arundinacea*
White clover – *Trifolium repens*
Winter rye – *Secale cereale*
Winter wheat – *Triticum aestivum L.*

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