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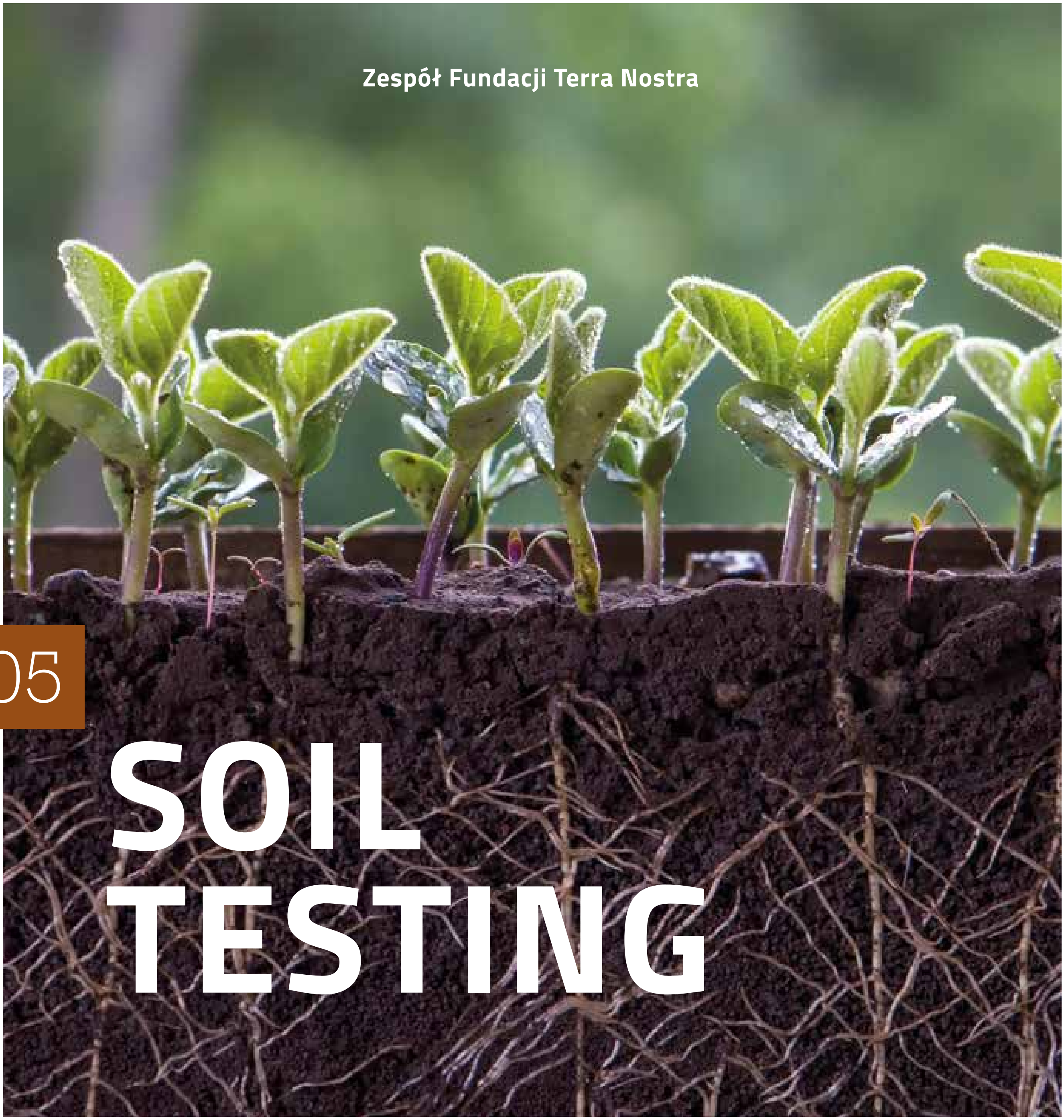

05

SOIL TESTING

CEE REGENERATIVE AGRICULTURE GUIDEBOOK

TERRA NOSTRA FUNDACJA
eit Food REGENERATIVE AGRICULTURE REVOLUTION
Co-funded by the European Union

CEE REGENERATIVE AGRICULTURE GUIDEBOOK SOIL TESTING

Author:
Zespół Fundacji Terra Nostra

Graphic design:
Maciej Wilgosiewicz
Piotr Krukowski
Agencja reklamowa Pixel Star

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SOIL TESTING

CEE REGENERATIVE AGRICULTURE GUIDEBOOK

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INTRODUCTION

5.1

Valuable food that ends up on our table has its origin in the soil.

Healthy soil can be considered a living organism. It provides the necessary mineral salts and water for plants, which in return provide the necessary nutrients for fungi, bacteria and other soil-dwelling organisms. They make up a small fraction of the soil weight, but nevertheless play a key role in maintaining soil health and its physical and chemical quality by affecting soil structure, organic matter decomposition and nutrient transformation. Awareness of this extraordinary interdependence between living and non-living elements of the soil and making sure that harmony between them is maintained is what guides the regenerative approach to building the quality and health of agricultural soils. Unfortunately, it is estimated that 33% of the world's land is moderately to severely degraded. The destruction of soil, and the ensuing decrease in their quality, is caused, among others, by intensive cultivation (using the wrong tools), pollution, climate change (drought resulting in water shortage) and improper fertilisation. Keeping it in good condition is crucial to feeding the world, as it is estimated that soil is the basis for the production of 95% of food intended for consumption.

Regenerative agriculture is a way of improving the condition of the soil. Its importance for the necessary soil strengthening, and thus improving its fertility, is increasingly more visible. The primary goal of regenerative agriculture is to restore and maintain the yield-generating potential of the soil by maintaining agricultural production that does not cause harm to the natural environment. Regenerative agriculture offers a number of benefits, such as the production of high-quality food and fodder, proper management of organic matter in the soil, improvement of biological, physical and chemical properties (pH in particular), increase in yield potential; protection of soil, water and air against pollution of agricultural origin, reduction of expenditures (plant protection products, mineral fertilisers), energy saving, reduction of CO_2 emissions.

SOIL AND ITS KEY PROPERTIES

5.2 To better understand how soil works, it's worth taking a closer look at it.

Soil is a natural, external and biologically active layer of the Earth's crust. It was made of weathered rock as a result of soil-forming processes that continued for thousands of years. It consists of mineral particles, decomposed organic matter, water and air. It is divided into the mineral and the organic fraction. Soil is a three-phase structure, made up of solids, liquids and gases.

Important soil quality parameters include its chemical and physical-chemical properties, such as: organic matter (organic carbon) content, total nitrogen, macronutrients easily assimilated by plants, that is phosphorus, potassium, magnesium, calcium and sulphur, pH (measured as KCl and/or H_2O), cation exchange capacity, degree of saturation with alkaline cations (Ca^{2+}, Mg^{2+} and K^+ Na^+), micronutrients such as iron, boron, copper, manganese and zinc, and electrical conductivity.

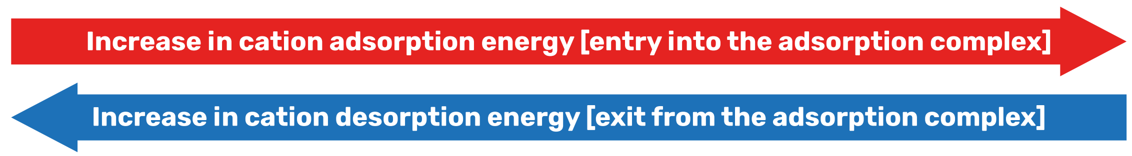
The soil has the adsorption capacity, that is the ability to retain various types of ions or substances that get into it or are already present within it. The quality and fertility of soils depend on the so-called **soil adsorption complex,** that is the most active, fragmented part of the solid phase of the soil, which affects the cation exchange capacity. As a result of adsorption, nutrients dissolved in the soil solution are not washed out (e.g. together with water soaking in after rainfall). Therefore, care for the adsorption complex is very important in building the fertility and productivity of agricultural soils.

The soil adsorption complex consists of mineral and organic components of the solid phase. These are clay minerals (e.g. illite vermiculite, montmorillonite) and organic matter together with humus (humic acids, fulvic acids, humins). It can therefore be concluded that the more of these components are present in the soil, the greater the capacity of the adsorption complex. They are dispersed in the soil in a colloidal form and are negatively charged in most cases. This charge enables the adsorption complex to retain positively charged ions (e.g. calcium Ca^{2+}, magnesium Mg^{2+} cations) because the opposite charges attract each other. The adsorption complex is also capable of non-exchangeable adsorption of some ions. This type of adsorption does not depend on the charge of the substances forming the complex and to a small extent determines the availability of nutrients for plants. The adsorption complex also shows the capacity to adsorb anions (e.g. chloride, nitrate (V), sulphate (VI)). However, this type of adsorption is much smaller than the adsorption of cations, because there are fewer positive charges (capable of adsorbing anions) in the complex than there are negative ones. Therefore, anions (e.g. NO_3^-) are adsorbed in relatively small amounts and are easily leached into the soil profile.

The adsorption complex acts as a warehouse or a waiting room for ions dissolved in the soil solution It is responsible for retaining and releasing various ions into the soil solution, including nutrients that are crucial for plant life. The ions released into the soil solution are replaced by other ions in an equivalent amount, which is why the adsorption complex is responsible for the exchange adsorption of ions. **Exchange adsorption involves the exchange of ions between the soil solution and the adsorption complex.** During the exchange reaction, a state of dynamic equilibrium is established between the amount and structure of cations present in the soil solution and the amount of the relevant ions in the adsorption complex. A high concentration of ions in the soil solution increases their adsorption, and so ions with high energy input (poorly adsorbed) can also penetrate into the adsorption complex (e.g. Na^+ if it is present in the soil in high concentration).

The sequence of entry and exit of cations into/from the adsorption complex is shown below:

$$Li^+ < Na^+ < NH_4^+ = K^+ < Mg^{2+} < Ca^{2+} < Al^{3+} < Fe^{3+} < H^+$$



H^+ shows the lowest energy input into the adsorption complex (it is easily adsorbed), followed by trivalent and divalent ions, and then by monovalent ions. Easily adsorbed cations (low energy input) are more difficult to remove from the complex (since they also have high energy output). The total amount of all ions adsorbed in the exchange is the cation exchange capacity (CEC)*.

** the cation exchange capacity in the soil is variable and correlated with soil pH. If soil pH is below 6, there is an excess of H^+ ions in the soil/water solution and many negative exchange places are occupied by acidic cations such as Al^{2+} and Fe^{2+}. As the pH of the soil increases as a result of the addition of Ca, Mg, K and Na, the Al and Fe ions combine with the negatively charged OH^- ions in the soil and water solution to form insoluble aluminium and iron oxides and release the negatively charged OH^- ions. The places in humus play a role in nutrient exchange. Soil with a high content of organic matter will have a low „effective" exchange capacity at low pH, as many of the negative exchange places will be filled with tightly bound Al and Fe. The addition of basic cations, especially calcium, will raise the pH and Ca^{2+} ions will displace Al and Fe through the „exchangeable" Ca.*

Humus is the primary indicator of soil fertility. **Soil humus is a very important part of soil organic matter, the total content of which can be measured by determining the total organic carbon content.** Organic matter is therefore a diverse mixture of all organic residues of plant or animal origin that end up in the soil and are decomposed and transformed there. From a biochemical point of view, humus is a part of organic matter, which is made of complex, amorphous substances (it is impossible to distinguish plant or animal cells in them). They are formed as a result of transformation of organic residues, mainly from plants, with the participation of soil organisms (e.g. bacteria, fungi) and small invertebrates, such as earthworms. They often occur in combination with the mineral phase of the soil. After the transformation of organic residue, the resultant humus fraction is formed by various organic and mineral-organic substances, accumulating in the soil or on its surface, which are the source of negative charges in the soil.

HUMUS PERFORMS A NUMBER OF IMPORTANT FUNCTIONS IN THE SOIL, AS IT DETERMINES:

- ***the capacity to retain and collect nutrients (adsorption capacity) - improves the storage and availability of nutrients and reduces their losses*;***
- ***water capacity and the ability to retain it - increases water retention and minimises the effects of drought (soils are more resistant to it);***
- ***stability of the soil structure - improves the soil structure, especially in the presence of Ca^{2+} ions, which prevents the loss of water and nutrients in light sandy soils and loosens compact soils, in which aeration thus improves. It prevents water and wind erosion of the soil;***
- ***biological activity - increases it by having a beneficial effect on the multiplication of beneficial soil microorganisms that determine the health of the soil;***
- ***colour and thermal properties of the soil – a darker colour increases the absorption of solar energy, which results in improved heating of the soil.***

** Humus can have the exchange capacity greater than even the highest CEC of clay minerals - the higher the level of humus in the soil, the greater the soil's CEC.*

Substances that form the humus fraction are also considered to be the most stable portion of organic matter in the soil, which is not as easily decomposed as fresh plant and animal residue, and therefore they constitute the largest part of organic matter. **To build humus reserves in soils, it is crucial to add the right amount of organic matter to the soil and protect its biological life.** Raw organic matter that is not yet processed, coming from compost, manure, or last year's crop residue, does not have significant capacity to absorb nutrients or retain water, until it is transformed into humus. The formation of humus requires the action of various soil organisms. When none of them can use organic matter as food, it becomes a very complex carbon structure that can hold and release multiples of its own weight as water and plant nutrients. In addition, humus prevents soil crusting (because it improves the stability of soil aggregates) and prevents rapid changes in pH (it has buffer properties). As the content of humus in the soil increases, the availability of toxic substances from the soil (from industrial waste, plant protection products) and harmful heavy metals

(cadmium, lead, aluminium) decreases. Humus has the ability to attract many of these harmful substances, immobilizing them and making them inaccessible (and thus less toxic) to plants and soil organisms. This is very important, because the increased content of potentially harmful substances in plants poses a threat to the health of consumers. Humus also has a large impact on nitrogen and phosphorus management in agricultural fields. Nitrogen is the most mobile element in the soil and humus prevents its leaching.

The preservation of humus as a resource is important not only in terms of maintaining the productive functions of the soil, but also from the point of view of the role of soil in the sequestration (capture) of carbon from the atmosphere and reducing the greenhouse effect. According to the EU's Mission Board Soil Health and Food, we currently see the depletion in organic carbon in the top layer of crop soils (0-20 cm) in EU countries, averaging 0.5% per year. The decrease in the content of organic carbon in arable soils results from the insufficient amount of ingredients to build stocks of organic matter in the soil, and from intensive cultivation. The main farming mistakes contributing to the loss of carbon from arable soils include the failure to use straw for fertilisation, incompetent use of the potential created by cover crops (cover crop stubble, winter crops and undersown crops), continuous and dramatically low share of legumes (soybean, lupin, pea, field pea, clover, alfalfa and other) in crop rotation and too intensive soil cultivation, which promotes the degradation of soil structure and rapid mineralization of organic residue. Unfortunately, the failure to tap into the potential of increasing soil fertility and productive is widespread. This should **change and a comprehensive new strategy for developing soil fertility, with particular emphasis on rebuilding carbon stock, should be introduced in agricultural practice. It is of seminal importance for soil quality.** One way to increase humus content in the soil is to add organic matter and improve soil life. This will ensure its proper decomposition and transformation. If the mineral balance in the soil is optimal, especially with an adequate supply of sulphur, any added fresh organic matter will tend to form stable humus.

18 elements (recognized to date) are required for proper plant growth. They are divided into **macronutrients** and **micronutrients**.

MACRONUTRIENTS	MICRONUTRIENTS
carbon, oxygen, hydrogen, nitrogen, phosphorus, sulphur, potassium, calcium, magnesium	**manganese, zinc, iron, boron, copper, nickel, chlorine, molybdenum, cobalt**

Other elements are also taken up by plants and may be needed to some extent to ensure the course of certain physiological functions.

It should be especially remembered that the **basic condition for proper plant nutrition is a balanced supply of minerals, and then their undisturbed availability for plants,** the disturbance being caused by mutual antagonisms and mutual blocking of elements at the stage of their uptake by plants. It should also be noted that when introduced to the soil in excess or unilaterally, they triggered the described phenomena in a particular way, e.g. Ca^{2+}.

Neutral (6.6 - 7.2) or slightly acidic (5.6 - 6.5) pH is generally accepted as the **optimum pH** for the growth of most crops. Appropriate pH values for a particular type and grade of soil provide plants with favourable conditions for the uptake of nutrients. On the other hand, in highly acidic soil, the biological activity of bacteria and actinomycetes decreases, the composition of the adsorption complex deteriorates, and large amounts of toxic aluminium and manganese are released into the soil solution, which results in a reduction in yields and deterioration of their quality. Similarly, for excessively alkaline soils, the conditions for the availability and uptake of nutrients change.

The most important **physical properties of** soil include: granulometric composition, structure, soil density, porosity, compactness, swelling and shrinkage, and functional properties, such as water, air and heat. The physical properties of soil are of great importance for the growth and yield of crops. In field conditions, **durable aggregate structure ensures the best physical condition of the soil.** It prevents excessive compaction, provides the soil with beneficial capillary pores, water retention pores and air pores. The durability of aggregates therefore indirectly affects the development of soil microorganisms, increases the biological activity of the soil by creating a stable environment for their existence, supplying them with water, nutrients and air. The stable structure creates appropriate conditions for germination, emergence and development of plants, affects the length of their roots and the density of the canopy. The waterproof aggregate structure protects the soil against surface crusting, increases rainwater infiltration, reduces the rate of surface runoff and water erosion. It should be noted that the **formation and stabilization of soil aggregates is the result of the interaction of many physical, chemical and biological factors,** with the precondition for the aggregation being the presence and flocculation of clay minerals and the presence of various fractions of soil organic matter. Therefore, it is worth remembering that **the soil structure stabilising the soil environment is also created by inorganic and organic soil fractions (so-called inorganic and organic binding agents). Inorganic** stabilizing agents include mainly clay minerals, polyvalent metal cations (Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+}, iron and aluminium oxides and hydroxides, calcium and magnesium carbonates. As regards **organic** compounds that stabilise soil, there are temporary binders, quickly degraded by microorganisms, including microbial and plant polysaccharides. Temporary binders are plant roots, mycelial hyphae and some fungi. In order for the durability of the structure to be maintained, those organic binders must be constantly supplied to the soil. Permanent binding agents consist of resistant aromatic humic substances bound to polyvalent metal cations and highly sorbent polymers. These organic fractions are more resistant to decomposition.

Water properties of the soil, especially the retention of useful (available) water for plants and water conductivity, shape the water balance of the soil and have a decisive impact on the conditions for the growth, development and yielding of plants. They determine the availability of water to the plant root system and its movement with dissolved nutrients to deeper genetic levels. The most important water properties include: actual soil moisture, field water capacity, retention of water available to plants and water conductivity.

The **biological indicators of soil quality include**, among others: plant yields, soil fauna count (earthworms, enchytras, insects, etc.), the microorganism count, C and N content in the microorganism, microbial respiration and enzymatic activity.

INFLUENCING THE QUALITY OF SOILS = INFLUENCING THE YIELD

5.3

In the face of current environmental challenges, it is necessary to ensure proper plant nutrition.

In view of the current environmental challenges related to frequent deficits of water available to plants, extremely high temperatures, maladjustment of species to the changing climate, conventional approach to widely understood cultivation and fertilization practices, **it is necessary to fully optimise and rationalize them in order to ensure proper plant nutrition.** This is how we will minimise the production of agricultural raw materials with a defective mineral composition and disturbed proportions between nutrients (so important from the nutritional point of view of plants and humans) and optimise yields. Importantly, it is **our duty not to disturb the soil balance. Only sustainable soil-related actions will help us achieve qualitatively sustainable yields.**

The key factors in proper plant include the appropriate content of nutrients in the soil in a form assimilable by plants, and, which is particularly important - the right proportions between minerals in the soil. The soil layer should be at the same time thick enough and loose enough, demonstrate appropriate stable water and air conditions and the proportions between water and air to ensure the supply of soil water with nutrients dissolved in it, and air access to the roots of crops and soil organisms.

The parallel involvement of physical, chemical, physical-chemical and biological factors is essential in building the health and quality of soils and plant yields. There are close cause-and-effect relationships between them, which determine soil fertility and capability. They are inextricably linked and interact with each other, and therefore they must be treated holistically.

An important element in the new approach to soil is understanding its functioning, but also the knowledge of new methods and ways to analyse it, and then the ability to ensure appropriate field practices being a logical consequence of the emergence of a new type of data.

CURRENT ASSESSMENT OF SOIL PROPERTIES IS THE BASIS FOR ITS REGENERATION

5.4

Due to poor soil management, the ionic balance between nutrients in the production chain from field to fork has been upset.

Nutrients depleted from the soil along with the harvest of crops are supplemented in the form of fertilizers, mainly mineral. These fertilizers are applied frequently and in a non-balanced way, disturbing the original ratio of ions present in the soil. Components depleted to a lesser extent by plants are not supplemented. The use of NPK mineral fertilization only, incorrectly referred to as "full" fertilization in practice, upsets the ionic balance in cultivated soils, which is a very unfavourable development*. It should be remembered, however, that we do not fertilize plants, but rather introduce fertilizers into the soil, and only later, depending on many parameters, including the balance between them, will they be taken up by the cultivated plants. The forgotten principle is that the soil is the primary source of minerals for plants, and fertilization should supplement those components that are present in the soil in insufficient amounts. The availability of nutrients for plants is a rather dynamic process. Some of the ingredients supplied with fertilizers may be permanently bound in the soil, leached, displaced or volatilized, and therefore, when determining the doses of fertilizers, their utilization factor should be considered.

** In fertilization, the law of the minimum developed by Justus von Liebig applies, stating that the basic parameters of the yield, its size and quality, are conditioned by the factor present in the smallest amount. In effect, if, in addition to high availability of most minerals for plants in the soil environment, one mineral is present in deficient amounts, it will cause a quantitatively low yield or its poor quality.*

Mineral ingredients interact with one other. This means that a high or too-low level of one blocks or prevents the uptake of another. The following impacts have been identified in the studies carried out so far (high and low level - limits the presence and uptake):

MINERAL INGREDIENTS INTERACT WITH ONE OTHER
(high and low level - limits the presence and uptake):

- ***CALCIUM - potassium, magnesium, boron, zinc, manganese, iron***
- ***POTASSIUM - magnesium, boron, calcium***
- ***PHOSPHORUS - potassium, zinc, copper, iron***
- ***NITROGEN - potassium, boron, copper***
- ***COPPER - iron, manganese***
- ***ZINC - iron***
- ***MOLYBDENUM - copper***
- ***MANGANESE - iron***

pH of the soil has a major impact on the presence and uptake of minerals. If pH is low (excessive soil acidity), the most available for plants are metallic microelements, especially iron and zinc, and the least available are macroelements - calcium and potassium. As a consequence, the growth of the root system is inhibited, the uptake of many minerals is limited, in particular of phosphorus, calcium, magnesium and molybdenum.

The solution for improving the condition of soils is regenerative agriculture, gaining in importance because of the need to improve the quality of soils, and so their fertility. Caring for the quality of soil will be the primary goal not only for farmers and farms, but above all for every producer, due to the growing importance of food environmental safety and ever tighter restrictions in this area.

SOIL TESTING IN REGENERATIVE AGRICULTURE

5.5

Soil testing is the basis for proper and effective farm management in the 21st century.

The determination of chemical and physical-chemical properties should be the basis for dosing fertilizers and optimising yields. Laboratory testing of soil is extremely important for agricultural chemistry. The selection of an appropriate testing method determines the achievement of an accurate and reliable result.

Soil, due to its diversity and the dynamic changes within it, requires the use of appropriate testing methods. Therefore, extended soil testing and diagnostics should be performed before any supplementation with fertilisers. It is necessary to find out what soil we are dealing with and at what level its regeneration starts.

The key element of the new approach to assessing the quality of its nutrients is to analyse its soil adsorption complex (CEC), and then to determine the degree of its saturation with cations, expressed as a percentage share of basic cations in the CEC base, i.e. Ca 2+, Mg 2+, K+, Na+ and H+ according to Williams*. The percentage of saturation with the base cations of calcium, magnesium, potassium and sodium and the ratio of these cations to each other is a measure of the capacity of soil to retain and release various elements and compounds, in particular positively charged nutrients. The capacity of the adsorption complex of different soils can be compared to a bucket: some soils are like a large bucket (high CEC), some are like a small bucket (low CEC). A sandy soil with a small organic content will have a very low CEC, while a clay soil with a high organic (as humus) will have a high CEC.

**From the 1920s to the late 1940s, William Albrecht conducted many experiments with varying ratios of nutrient cations, such calcium, magnesium, potassium and sodium, in soils. He and his colleagues, working at the University of Missouri's Agricultural Experimental Station, concluded that the strongest, healthiest, and best-nourished crops were grown in soil where the CEC was saturated to approximately 65% calcium, 15% magnesium, 4% potassium and 1% to 5% sodium (this does not need to add up to 100%). This ratio not only provides lavish levels of those nutrients for crops and soil life, but also strongly influences soil structure and pH.*

SOIL SAMPLING

5.5.1

The process of soil sampling impacts testing reliability.

The consequences of poorly prepared soil samples are distorted results, interpretations, and fertilization recommendations. The sampling method proposed below eliminates those risks. It is crucial to move away from the current practice of sampling every four years in favour of annual sampling.

SOIL SAMPLES ARE COLLECTED:

- ***from the same place, via GPS coordinates,***
- ***at the same time of year, which ensures the comparability of soil composition over time,***
- ***by the same person, which ensures the uniformity of the samples taken.***

The microprofile of soil sampling is also important, stipulating division into layers enabling the determination of a dynamic view of soil changes vertically in a given place in the field. Three layers of soil taken from the same location and the same field, sampled annually, provide the basis for reasonable fertilizer management, enabling flexible and informed implementation of plant and soil nutrition with full respect for the changing environment and food quality requirements.

The collected soil is tested as soon as possible after its collection.

By analysing data from annual tests, we can determine trends for a given parameter in a four-year window. This allows quick and targeted interventions to influence the forecasted changes in the horizontal system (period of 1-2-3-4 years) and enables proper fertilization.

SOIL TESTING

5.5.2

The starting point for farmers who want to engage in regenerative farming is a reliable estimation of the CEC of the soil they work with.

The recommended soil test for nutrient balance is **the Mehlich 3 test**. The Mehlich 3 or M3 solution is a strongly acidic extractant (pH of 2.5). The test makes it possible to measure not only the amount of nutrients that are readily available to plants, but also those that are potentially available, the so-called reserves.

For complete results, perform the Mehlich 3 soil test for all of the following minerals:

Primary cations	Primary anions	Secondary elements
Calcium	Phosphorus	Boron
Magnesium	Sulphur	Iron
Potassium		Manganese
Sodium		Copper
		Zinc

The elements presented in the table are nutrients for plants, whose effects are well understood, and it is important that all of them are present in the soil in the right amounts. It is not necessary to know the amounts of micronutrients to get started with regenerative farming, as ordinary soil tests do not even measure them. However, **in order to manage your farm and soil responsibly, it is recommended to know the full spectrum of its capacity and limitations.**

RECOMMENDED SOIL TESTING PACKAGE FOR THE REGENERATIVE APPROACH:

- *pH in KCl /H_2O, pH, liming needs in mg/kg*
- *C-org content, humus [in %]*
- *conductivity [in μS/cm]*
- *Mehlich 3 test for the following ingredients: P, K, Mg, Mg, Ca, B, Mn, Cu, Zn, Fe, S-SO_4, S, Ca, Mg, K, Na, H, Al; determination of CEC [in me/100g of soil]*

PROPER INTERPRETATION AND UTILISATION OF SOIL TEST RESULTS IN REGENERATIVE CROP MANAGEMENT OFFERS:

- *reduction of production costs*
- *more efficient and effective production respecting the environment*
- *long-term production stability*
- *production of sustainable food*


Cu
Zn
Mo
Mn
N
P
B
S
Ca
Fe
K
Mg
Cl

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