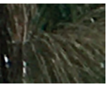
BOLETIM DE PESQUISA E DESENVOLVIMENTO

01

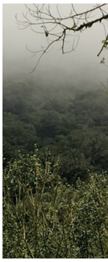
ISSN 1806-3322
June / 2021

Fertility concepts and adequate management for soils in tropical regions










Embrapa

ISSN 1806-3322
June /2021

Brazilian Agricultural Research Corporation
Embrapa Territorial
Ministry of Agriculture, Livestock and Supply

BOLETIM DE PESQUISA E DESENVOLVIMENTO
01

Fertility concepts and adequate management for soils in tropical regions

Carlos Cesar Ronquim

Embrapa Territorial
Campinas, SP
2021

Responsible for content and publication

Embrapa Territorial
Av. Soldado Passarinho, nº 303
Fazenda Chapadão
13070-115, Campinas, SP
Fone: (19) 3211.6200
www.embrapa.br/territorial
www.embrapa.br/fale-conosco/sac

Originally published under the title '*Conceitos de fertilidade do solo e manejo adequado para as regiões tropicais*', 2nd edition
ISSN 1806-3322

1st edition
1st edition (2021): on-line

Executive edition
Suzi Carneiro and Bibiana Teixeira de Almeida

Text revision (Portuguese)
Bibiana Teixeira de Almeida

Translation (into English)
Bibiana Teixeira de Almeida

Bibliographic standardization
Vera Viana dos Santos Brandão

Grafic design (Collection)
Carlos Eduardo Felice Barbeiro

Layout
Suzi Carneiro

Cover
Suzi Carneiro, with images by Carlos Cesar Ronquim

Cataloging-in-Publication (CIP) Data
Embrapa Territorial

Ronquim, Carlos Cesar.

Fertility concepts and adequate management for soils in tropical regions / Carlos Cesar Ronquim, translated by Bibiana Teixeira de Almeida. - Campinas: Embrapa Territorial, 2021. 34 p.: il. ; (Boletim de Pesquisa e Desenvolvimento / Embrapa Territorial, ISSN 1806-3322; 01).

Original title: Conceitos de fertilidade do solo e manejo adequado para as regiões tropicais. 2nd ed.

1. Fertilizer application. 2. Alternative agriculture. 3. Soil amendment. 4. Sustainability. I. Almeida, Bibiana Teixeira de. II. Title. III. Series.

CDD 631.4913

Vera Viana dos Santos Brandão (CRB 8/7283)

Conteúdo

Fertility concepts and adequate management for soils in tropical regions

Carlos Cesar Ronquim[1]

Abstract – Global agricultural production will have to increase by 70% until 2050 to provide for the increasing food supply needed for a growing population, with growing revenues and a shifting, protein-based diet (FAO, 2017). This production will demand over 120 million hectares of agricultural lands, and must rely on sustainable agricultural intensification and productivity increase in areas which are already used for agricultural purposes. Singularities of tropical agriculture require detailed knowledge of chemical and physical properties of the soils, with the aim of properly using supplies and of adequately maintaining soils, to render more profitable productions. Thus, evaluating the chemical fertility of soils is essential to define adequate amounts and types of fertilizers, corrective dressings and management practices to be used, in order to maintain or recover soil productivity. The purpose of this publication is to introduce the main concepts involved in soil fertility, to relate them to the most adequate management practices for tropical regions, and thus offer an elementary resource for understanding the correlations between soil fertility concepts and agricultural productivity.

Keywords: fertilization, ecological agriculture, soil amendments, sustainability.

[1] Carlos Cesar Ronquim, Agronomist, Ph.D. in Ecology and Natural Resources, researcher at Brazilian Agricultural Research Corporation (Embrapa Territorial), Campinas, SP

Conceitos de fertilidade do solo e manejo adequado para as regiões tropicais

Resumo – A produção agrícola mundial precisará aumentar 70% em relação aos níveis atuais para atender, em 2050, o crescimento da demanda de alimentos resultante de aumento da população, rendimentos crescentes e mudança para dietas ricas em proteínas (FAO, 2017). Essa produção demandará mais de 120 milhões de hectares de terra e, para ocorrer de forma sustentável, dependerá de intensificação agropecuária e aumento da produtividade das áreas já cultivadas. Ante as peculiaridades da agricultura nas regiões tropicais, torna-se necessário conhecer detalhadamente as características e propriedades químicas e físicas dos solos, objetivando seu manejo adequado, o uso mais apropriado de insumos e produções mais rentáveis. Avaliar a fertilidade química dos solos é de suma importância para definir quantidades e tipos de fertilizantes, corretivos e manejo geral que devem ser aplicados ao solo visando à manutenção ou à recuperação de sua produtividade. O objetivo desta publicação é apresentar os principais conceitos da fertilidade dos solos, relacioná-los às formas de manejo mais adequadas para as regiões tropicais e constituir, assim, um texto básico para a compreensão da relação entre conceitos de fertilidade do solo e produtividade agropecuária.

Palavras-chave: adubação, agricultura ecológica, correção do solo, sustentabilidade.

Context

Evolution in production technologies for tropical soils, along with increases in crop yields over the last decade created an opportunity for reediting this *Boletim de Pesquisa e Desenvolvimento*[2], with the aim of keeping its contents aligned with the continuous process of improving agricultural productivity, especially in Brazil. This publication offers information on the main concepts related to soil fertility and provides guidance on the most adequate management practices for soils in tropical regions. These practices aim not only productivity increase, but also the sustainability of production systems. Originally published in 2010, this new edition has been revised. Boasting a high number of downloads in Embrapa's repositories, this publication is aimed at a general audience, which is composed mainly by farmers, researchers and students involved in the agriculture and forestry segments. Additionally, this new edition has been published in two languages, Portuguese and English, expanding its reach to a wider range of readers, who now have an extra reference for the correct management of tropical soils.

Soil mineral nutrients essential to plants

Macronutrients - nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) -, also referred to as main nutrients, are absorbed by the plant in greater amounts than micronutrients - boron (B), zinc (Zn), copper (Cu), iron (Fe), molybdenum (Mo), chlorine (Cl) and manganese (Mn) -, which are referred to as trace elements. Both are components of the organic matter (OM) in the substrate where the plants grow, and are also found dissolved in the soil. Other nutrients – selenium (Se), silicon (Si), cobalt (Co), sodium (Na), aluminum (Al), vanadium (V) and nickel (Ni) – are considered beneficial, because they stimulate growth, but are not essential or are essential only to certain plant species or under specific conditions.

[2] Research and Development Bulletin, a regular series published by Embrapa’s centers. – Trans.

One or several of these nutrients may be nearly absent in the soil, or may be present, but in forms in which the plants' roots cannot absorb them. On the one hand, soils must be well managed to make these elements available. On the other hand, these nutrients must be replenished if absent in the soil. The average contents of mineral elements in the soil and in the biomass of terrestrial plants is shown in Table 1.

Table 1. Average contents of mineral elements (g/kg of dry matter)* in the soil and in the biomass of terrestrial plants, and average demand for each mineral element according to Larcher (2004), based on several authors.

Element	Average concentration in the soil	Threshold concentration in the plant	Demands
Si	330	0.2–10	
Al	70	0.04–0.5	
Fe	40	0.002–0.7	approx. 0.1
Ca	15	0.4–15	3–15
K	14	1–70	5–20
Mg	5	0.7–9	1–3
Na	5	0.02–1.5	
N	2	12–75	15–25
Mn	1	0.003–1	0.03–0.05
P	0.8	0.1–10	1.5–3
S	0.7	0.6–9	2–3
Sr	0.25	0.003–0.4	
F	0.2	up to 0.02	
Rb	0.15	up to 0.05	
Cl	< 0.1	0.2–10	> 0.1
Zn	0.09	0.001–0,4	0.01–0.05
Ni	0.05	up to 0.005	
Cu	0.03	0.004–0.02	0.005–0.01
Pb	0.03	up to 0.02	
B	0.02	0.008–0.2	0.01–0.04
Co	0.008	up to 0.005	
Mo	0.003	up to 0.001	< 0.0002

*For dry matter percentage (%), the values in the table must be divided by 10.

Nutrients are usually replenished using mineral chemical fertilizers, OM, or minerals extracted from mines or from the air (the latter in the case of biological nitrogen fixation). Organic matter contains nearly all macro and micronutrients. Besides, it conveys a better structure to the terrain, increasing its fertility. Mineral fertilizers, as opposed to OM, have strong concentrations of highly soluble nutrients which may be rapidly absorbed by plants or may more easily leach[3].

Mineral fertilizers sold for crop fertilization may be simple (contain one or more macroelements) or compound fertilizers (a mixture of simple fertilizers). Compound fertilizers are referred to by their formulas (e.g., 4–14–8, 10–10–10, 20–5–20). These numbers indicate the nitrogen, phosphorus and potassium (N–P–K respectively) percentages in the chemical fertilizer. It is important that all nutrients are balanced in the soil: adding one nutrient without taking into account the situation of the other ones and the crop's specific characteristics may lead to problems during harvest. In tropical regions, sufficient amounts of OM in the soil are decisive for maintaining a good nutrient balance in the soil.

Aside from the macro-and micronutrients in the soil, plants absorb carbon (C), hydrogen (H) and oxygen (O). On the one hand, these elements may not be considered truly mineral, since they are primarily obtained from water and carbon dioxide. On the other hand, they are essential components of all organic molecules. Without them, living organisms simply would not exist. Atmospheric nitrogen may also be incorporated by plants by means of the action of symbiotic microorganisms.

Liebig (1803–1873), a german chemist, stated that most of the C within plants comes from the carbon dioxide (CO_2) available in the atmosphere, that H and O come from water, and that plants indiscrimenately absorb everything from the soil, but excrete through their roots those substances which are not essential to them (Liebig, 1972).

It is also Liebig's the Law of the Minimum, according to which the scarcest mineral substance is the limiting factor for plant growth and yield. However, yield is limited not only by a mineral substance. For a plant's metabolism to

[3] Leaching: process of removal of soluble substances from the soil through drained water.

be balanced, produce high amounts of dry matter and show unrestrained development, it is not enough that its main nutrients and trace elements are available in adequate amounts, they must also be absorbed at balanced rates.

In tropical soils with reduced buffering capacity[4], the application of fertilizers may easily produce an imbalance. This condition may be avoided by maintaining an adequate level of OM in the soil. Organic matter increases the soil's buffering capacity and decreases risks of mineral imbalances caused by random fertilization.

Cation exchange capacity (CEC), sum of bases (SB) and base saturation (V%)

Due to the electrically charged surface of colloidal clays[5], humic substances[6] and iron and aluminum sesquioxides[7] (main components of the mineral fraction of tropical soils), polarized ions and molecules are attracted to and form reversible bonds with these components.

Mineral clays, humic substances and iron and aluminum oxides feature such exchange surfaces and are the main colloids involved in cation exchange capacity (CEC) in tropical soils (Table 2). Clay colloids are fractions smaller than 0.001 mm or 1µ. Organic colloids become humus; they are products of the decomposition of OM, and are transformed biologically. Due to the higher amount of negative charges in this colloids in comparison to positive charges, the ions adsorbed are mostly cations. However, these colloids do have a few sites with positive charges and which may attract anions (especially in iron and aluminum oxides).

[4] Buffering capacity: soil's capacity to resist to sudden pH changes. Requires higher doses of limestone to achieve the desired base saturation (V%) or pH. Soils richer in organic matter or with higher cation exchange capacity (CEC) show higher buffering capacity

[5] Colloids: soil particles of reduced size (between 10^{-4} and 10^{-7} cm). Their surface charges may retain nutrients (ions) in exchangeable format.

[6] Humic substances: colloidal substances that aggregate soil. They are produced by the decomposition of straw by bacteria and fungi under aerobic conditions, and have aggregation capacity.

[7] Fe and Al sesquioxides: are part of the colloid fraction of the soil. They are poorly crystallized, but not amorphous.

Cation exchange capacity (CEC) in a given soil, clay or organic-matter humus depicts the whole amount of cations in permutable condition (Ca^{2+} + Mg^{2+} + K^{+} + NH_4^{+} + H^{+} + Al^{3+}) retained on the surface of these materials. CEC depends on the amount and type of clay and OM available.

Table 2. Cation exchange capacity (CEC) for some soil colloids under tropical conditions. Adapted from Mello et al. (1983).

Colloid	CEC ($mmol_c/dm^3$)
Humic substances	1,500 – 5,000
Vermiculite*	1,000 – 1,500
Montmorillonite*	500 – 1,000
Allophane*	250 – 700
Illite*	100 – 500
Kaolinite*	50 – 150
Fe and Al oxides	20 – 50

*Mineral clays.

A soil with high clay content may retain more exchangeable cations than a soil with low clay content. CEC also increases as the OM content increases. Soil CEC is influenced by the type and amount of clay and OM and by the specific surface, and is also strongly altered by pH. This effect is mainly caused by the dissociation of organic radicals or iron and aluminum sesquioxides, as well as by the detachment of charges occupied by Al^{3+}, Fe^{2+} and Mn^{+} in OM.

The results of CEC routine analyses to evaluate soil fertility, including those of analyses made within farmers' lands, are provided in centimoles of charge per cubic decimeter of soil ($cmol_c/dm^3$) or millimoles of charge per cubic decimeter of soil ($mmol_c/dm^3$), which is equivalent to 10 $cmol_c/dm^3$.

Ion-exchange capacity is, therefore, a degree of the soil's capacity to release several nutrients, favoring the maintenance of its fertility for a longer period and diminishing or preventing the occurrence of toxic effects produced by fertilizer application.

Soils' negative charges are divided into permanent charges and pH-dependent charges. Permanent charges exist within the structure of minerals and, for this reason, are always operational. pH-dependent charges, however, may be effective or not, depending on the environment's pH.

A soil is considered good for plant nutrition when most of the soil's CEC is occupied by essential cations, such as Ca^{2+}, Mg^{2+} e K^{+}. However, if a large part of the CEC is occupied by potentially toxic cations, such as H^{+} and Al^{3+}, the soil is considered poor (Table 3).

Tabela 3. Cation exchange capacity (CEC) and its empirical implications. Adapted from Potash & Phosphate Institute (1995).

High CEC	Low CEC
High clay percentage or high organic matter (OM) content	Low clay percentage or low OM content
Higher amount of limestone needed to elevate pH	Lower amount of limestone needed to elevate pH
Higher nutrient retention capacity at a given depth	Nitrogen and potassium leaching is higher
Higher water retention capacity	Lower water retention capacity

In most acid tropical soils, CEC has a predominance of Al (Al^{3+}). Low CEC values indicate a low capacity of the soil to retain exchangeable cations. In such cases, neither fertilization nor liming should be made using large amounts at once; they should be applied in phases, to avoid greater losses by leaching.

CEC may be expressed as Total CEC when all exchangeable cations in the soil are considered (Ca^{2+} + Mg^{2+} + K^{+} + NH_4^{+} + H^{+} + Al^{3+}). However, H^{+} is removed from the adsorption surface only by means of direct reactions with hydroxyls (OH^{-}), thus producing water ($H^{+} + OH^{-} \rightarrow H_2O$). When the H^{+} ion is not taken into consideration in the CEC, it is known as Effective CEC. Soils may display high Total CEC values (for example, 100mmol$_c$/dm^3), but a significant part of their negative charges (for example, 60%) may be adsorbing H^{+} ions. In such cases, Effective CEC would be only 40 mmol$_c$/dm^3.

Many tropical soils also display positive charges, although negative charges are predominant in most of them. Even in soils featuring considerable amounts of positive electric charges, the presence of OM, which is entirely formed by negative, pH-dependant charges, leads to a final balance of more negative charges in the soil's top layers. There is no completely defined mechanism to explain anion retention by the soil. Iron and aluminum sesquioxides adsorb a few anions by means of the generation of positive charges. Ion exchange or adsorption in the form of anions may occurr, for example, with: NO^{3-}, PO^{4-}, HPO_4^{2-}, $H_2PO_4^-$, HCO^{3-}, SO_4^{2-}, Cl^-. However, this retention is not significant for pH values above 6.0.

The sum of exchangeable bases (SB) for a soil, clay or humus is the sum of permutable cation contents, except for H^+ and Al^{3+} ($SB = Ca^{2+} + Mg^{2+} + K^+$) and their values are expressed as $mmol_c/dm^3$ or $cmol_c/dm^3$.

SB hints at the number of negative charges occupied by bases in the colloids. When compared to effective CEC and exchangeable Al, SB enables calculating Al saturation and BS percentages in the CEC. When compared to CEC at pH 7.0, it enables evaluating the SB percentage (V%) for this CEC.

Base saturation (V%, Equation 1) is the name given to the sum of exchangeable bases expressed in cation exchange capacity percentage. This parameter reflects the percentage number of points for potential cation exchange in the soil colloidal complex which are occupied by bases.

$$V(\%) = 100 * SB \div CEC$$

or

$$V(\%) = 100 \text{ x } (Ca^{2+} + Mg^{2+} + K^+) / Ca^{2+} + Mg^{2+} + K^+ + H^+ + Al^{3+} \qquad (1)$$

The CEC value used in the formula is the Total CEC.

An excellent indicator of general soil fertility conditions, V% is even used to supplement soil names, which may be divided according to base saturation into:

- eutrophic soils (fertile), V% ≥ 50%, which feature high bases values – especially calcium, which favorably influences root growth.
- dystrophic soils (little fertile), V% < 50%. Some dystrophic soils may be very poor in Ca^{2+}, Mg^{2+} and K^+, and display high exchangeable Al contents. They may even reach an aluminum saturation (m% – Al

saturation %) superior to 50%, in which case they are considered as alic soils (very poor): exchangeable Al ≥ 3 $mmol_c/dm^3$ and m% ≥ 50%.

A low V% index means that small amounts of cations, such as Ca^{2+}, Mg^{2+} and K^+ are saturating the colloids' negative charges, and that most of them are being neutralized by H^+ and Al^{3+}. In this case, the soil is likely to be acid, and may even contain Al levels which are toxic to plants. This situation may be common in large tropical areas. Most crops yield good productivities in soils whose V% values range between 50% and 80% and pH values range between 6.0 and 6.5.

Aluminum saturation percentage, or m% (Equation 2), expresses the effective CEC fraction occupied by exchangeable Al (exchangeable acidity). In practical terms, it reflects the percentage of soil negative charges which are occupied by exchangeable Al. It is a form of expressing aluminum toxicity.

$$m\% = 100 \text{ x } Al^{3+}/Ca^{2+} + Mg^{2+} + K^{+} + Al^{3+} \quad (2)$$

Its value is expressed as $mmol_c/dm^3$ ou $cmol_c/dm^3$.

Soil reaction

Soil reaction is the degree of acidity or alkalinity of a given soil. Soil reaction is linked to a soil's fertility, because several important conditions – such as structure, mineral solubility, nutrient availability[8], microorganism activity and ion absorption by the plant – are influenced by soil reaction.

Soil reaction depends on the concentrations of H^+ ions both in the soil solution (momentary acidity) and adsorbed in exchangeable substances (potential acidity). Acid soils are common in tropical regions, where the high rainfall rates cause alkaline elements, notably Ca^{2+} and Mg^{2+}, to leach from the upper layers by waters containing CO_2, and to be replaced by H^+ ions in the colloids.

[8] Nutrient availability: nutrients that may be absorbed by the plants' roots. A fraction of the total contents of a nutrient in the soil solution or which may rapidly pass into the solution.

Soil acidification is a natural chemical process. All soils 'age' or undergo weathering, and acidification is part of this natural ageing process. Because Brazil, like other tropical countries, is located in a tropical region, in which rainfall rates and temperatures are high throughout the year, Brazilian soils are older and therefore more acid.

A given soil may become more acid as it is used for growing crops. Thus, alkali ions such as Ca^{2+}, Mg^{2+} and K^{+} are removed, normally absorbed by the crops, and may be replaced by Al^{3+}. Acidification of soils used for growing crops may also occur by means of fertilization, especially using nitrogen fertilizers. An example is shown in Equation 3.

$$2\,NH_4^{+} + 3\,O_2^{-} \rightarrow 2\,NO_2^{-} + 2\,H_2O + 4H^{+} \qquad (3)$$

(Ammoniacal N) (N dioxide) (acidity)

Expression and interpretation for soil reaction

pH (potential of hydrogen) indicates the amount of hydrogen ions (H^{+}) in the soil. Thus, a soil is acid if it contains high amounts of H^{+} ions and few calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^{+}) ions adsorbed in its colloidal exchange complex.

pH provides clues to the soil's general chemical conditions. Soils of high acidity (low pH values) generally display: poor alkali rates (mainly calcium and magnesium); high aluminum rates; manganese excess; high phosphorus fixation in soil colloids; potassium leaching trend; and deficiency of some micronutrients. A soil's pH indicates its biological-physical-chemical situation and, as such, considering only direct chemical effects to the roots would be deceiving.

Soil correction using liming

Correction, or liming[9], of tropical soils must have an effect on the sum of bases (SB), and consequently increase nutrient availability and exchange complex[10] for the plants and the effective CEC value. Correction by liming also saturates the exchange complex with calcium and magnesium and increases pH up to a level at which Al becomes nearly unavailable to the crops.

To correct soil acidity, an element that releases anions, forms a weak acid with hydrogen, and provides calcium or calcium and magnesium to the plant must be used. The materials employed to correct acidity in tropical soils (limestone) are naturally available in the form of rocks, which are ground and sieved to be applied to the soil. When applied to the soil, limestone forms Ca^{2+}, Mg^{2+} and HCO_3^- ions (by solubilization and dissociation). The latter reacts with water to form hydroxyl ions (OH^-), water and carbon dioxide (CO_2). Hydroxyls react to the adsorbed Al^{3+} and H^+ ions to form insoluble aluminum hydroxide (neutralization step) and water (toxic aluminum immobilization step), and release the charges previously occupied by these elements. These charges are then occupied by Ca^{2+} and Mg^{2+} ions.

- Limestone solubilization and dissociation:

$$CaCO_3 \text{ (insoluble)} + H_2O \rightarrow Ca^{2+} + HCO_3^- + OH^- \text{ (soluble)}$$

$$MgCO_3 \text{ (insoluble)} + H_2O \rightarrow Mg^{2+} + HCO_3^- + OH^- \text{ (soluble)}$$

$$CaO \text{ (insoluble)} + H_2O \rightarrow Ca^{2+} + 2OH^- \text{ (soluble)}$$

$$MgO \text{ (insoluble)} + H_2O \rightarrow Mg^{2+} + 2OH^- \text{ (soluble)}$$

- Acid neutralization in the soil:

$$HCO_3^- + H^+ \rightarrow CO_2 + H_2O$$

$$H^+ + OH^- \rightarrow H_2O$$

[9] Liming: application of amendments (limestone) to correct soil acidity.

[10] Exchange complex: soil charges used in ion exchange processes.

- Insolubilization of exchangeable toxic aluminum in the soil:

$$Al^{3+}\ \text{(soluble)} + 3OH^- \rightarrow Al(OH)_3\ \text{(insoluble)}$$

After limestone is applied, exchangeable aluminum is neutralized, and base saturation (V%) increases. Soil pH increases as part of the adsorbed hydrogen is neutralized.

For this reaction to occur, limestone must be thoroughly mixed to the substrate, to foster contact between all particles. The soil must be moist, so that the limestone applied to it is solubilized. Limestone must be applied considering enough time for it to react to the soil. Most limestones in the market require a period of at least three months for complete reaction.

Liming offers several benefits, such as pH increase and even the betterment of physical properties of some soils, neutralization of toxic aluminum and manganese, increase in calcium and magnesium rates, increase in phosphorus and molybdenum availability, increase in microorganism activity.

The safest criterium for limestone dosage recommendation is that which intends to increase the soil's base saturation percentage (V%) to an adequate level for crops in tropical soils. The amount of limestone is calculated (Equation 4) with the aim of increasing the percentage of cations that influence CEC values, usually 70% (for Brazilian South and Southeast regions) or 50% (for Brazilian Cerrado savannas).

$$NC = T\,(V_2 - V_1) \div TRNP \div 10 * p \qquad (4)$$

NC = need for lime, in tons of limestone per hectare.

T = CEC = cation exchange capacity ($mmol_c/dm^3$).

V_2 = desired base saturation % (between 50 and 70, depending on the crop).

V_1 = base saturation % detected by soil analysis.

TRNP = total relative neutralizing power for limestone (informed by the product's supplier). Variable according to CaO and MgO contents and to the product's grain size. Since CEC used was measured in $mmol_c/dm^3$, the TRNP value must be divided by 10 (as it is in the formula).

p = limestone incorporation depth factor (1 for 0 – 20 cm or 1.5 for 0 – 30 cm).

For a very long time, pH determined in water was the standard method for fertility analyses. However, when the samples are collected moist (which is common), there is risk of increased concentration of some salts over the time encompassing transportation, storage and preparation of the samples before analysis. When this happens, pH detection is affected. To avoid such problems, in several places pH readings were performed using a diluted salt solution ($CaCl_2$), which produces more stable readings. This method reduces or prevents seasonal variations (the same soil may display a lower pH in water during the dry season when compared to the rainy season), and may also reduce the effects of fertilizations using strong salts on pH readings. The interpretation adopted for pH values in $CaCl_2$ is shown in Table 4.

Table 4. Limits for the interpretation of soil acidity classes. Based on Tomé Júnior (1997).

Acidity	pH in $CaCl_2$ solution
Very high acidity	< 4.3
High acidity	4.4 – 5.0
Average acidity	5.1 – 5.5
Low acidity	5.6 – 6.0
Very low acidity	6.1 – 7.0
Neutral	7.0
Alkaline	> 7.0

However, for farmers in regions which are destitute of laboratories for soil analyses, pH detection in water is of great value, because it is a practical, simple and economic method.

Balance in nutrient absorption

Nutrients in the soil are interconnected and their proportions are strictly related. For each nutrient, excess is determined against the amounts of the other elements found in the soil, and deficiencies are always considered in terms of the element found at its lowest level at the moment (Table 5).

Table 5. Main connections between macronutrients added in excess to the soil which may cause inhibition of micronutrients and phosphorus. Adapted from Bergmann (1973).

Nutrient in excess	Main deficiency induced
NH_4	Cu
NO_3	Mo
P	Zn
K	B
Ca	Mn
Mg	Cu
S	P

Interactions among nutrients may be negative (inhibition) or positive (synergism). In inhibition situations, the presence of an element contributes to a decrease in the absorption of another element. In synergism situations, the presence of an element favors the absorption of another element, thus producing a beneficial effect for the plant (Table 6).

Since soil solution features a quite heterogeneous range of ions, the presence of an ion may modify the absorption of another. Therefore, maintaining these cations at balanced rates in the soil by means of adequate liming and fertilization is a basic principle to avoid deficiencies of some of them in the crops as a result of the aforementioned processes.

Table 6. Main connections between the effects of an ion on the absorption of another. Adapted from Malavolta et al. (1989).

Ion	Inhibition
Mg^{2+}, Ca^{2+}	K^+
$H_2PO_4^-$	Al^{3+}
K^+, Ca^{2+}	Al^{3+}
$H_2BO_3^-$	NO_3^-, NH_4^+
K^+	Ca^{2+} (high concentration)
SO_4^{2-}	SeO_4^{2-}
SO_4^{2-}	Cl^-
MoO_4^{2-}	SO_4^{2-}
Zn^{2+}	Mg^{2+}
Zn^{2+}	Ca^{2+}
Zn^{2+}	$H_2BO_3^-$
Fe^{2+}	Mn^{2+}
Zn^{2+}	$H_2PO_4^-$
Cu^{2+}	MoO_4^{2-}
Ion	**Synergism**
K^+	Ca^{2+} (low concentration)
MoO_4^{2-}	$H_2PO_4^-$

Use of agricultural gypsum

After a liming procedure, limestone usually does not easily seep through the soil profile. As a result, acidity is corrected only at the soil's surface, not at its depth. Thus, root development becomes difficult in soil layers deeper than that to which limestone was incorporated. Plants are consequently less capable of absorbing soil nutrients.

The use of agricultural gypsum ($CaSO_4.2H_2O$) controls this problem, because its accompanying ion, SO_4^{2-}, favors that Ca^{2+} seeps through the soil profile. This seeping causes: stronger participation of Ca^{2+} and less strong participation of Al^{3+} in the exchange complex, neutralization of excess aluminum, greater development of the root system at deeper layers and consequent increase in drought resistance. Unlike limestone, agricultural gypsum has almost no effect on soil pH. The reactions are briefly described below.

- Partial dissociation of gypsum at the soil surface

$$CaSO_4 \rightarrow Ca^{2+} + SO_4^{2-} \text{ (nearly 65\% of the total)}$$

- Solubilization

$$CaSO_4 \text{ (sólid)} \rightarrow CaSO_4 \text{ (neutral and soluble, nearly 35\% of the total)}$$

- Leaching of soluble gypsum

$$CaSO_4 \text{ (neutral)}$$

- Dissociation at depth

$$CaSO_4 \rightarrow Ca^{2+} + SO_4^{2-}$$

- Neutralization of toxic Al at depth

$$X - Al^{3+} + Ca^{2+} \rightarrow X - Ca^{2+} + Al^{3+}$$

$$Al^{3+} + SO_4^{2-} \rightarrow AlSO_4^{+} \text{ (not toxic)}$$

Gypsum application to tropical soils is recommendable under such conditions: calcium rates below 5 $mmol_c/dm^3$ and/or aluminum saturation (m%) higher than 40% in the layers below 20 cm.

The amount of gypsum to be applied is calculated using the formula shown in Equation 5.

$$NG=(4 \text{ to } 6)*\text{clay content} \quad (5)$$

NG = need for gypsum (kg/ha).

Clay content in the soil in g/kg.

Aluminum in the soil

The highest the kaolinitic clay content in the soil, the highest its the aluminum content, because aluminum is a predominant part of this mineral clay (1:1)[11]. When clay decomposes, Al^{+3} is released from octahedral layers. This Al^{+3} may remain on the surface in an exchangeable format (displacing H^{+} from the soil's adsorption sites) or may pass into the soil solution. If absorbed, aluminum may change the physiology and morphology of the plant.

Aluminum in the soil is considered the worst enemy of all crops. However, for some Brazilian Cerrado savanna tree species, native such as *Vochysia tucanorum* Mart., or grown such as *Ilex paraguariensis* A.St.-Hil., which are adapted to acid soils with strong Al^{3+}, Al saturation, Al stimulates root growth and benefits these plants' development.

Aluminum oxide effectively contributes to the structure of tropical soils, and is therefore very beneficial. If exchangeable aluminum does not surpass a given percentage of the cations in the effective CEC (depending on the soil's texture) – 40% of cations –, it will possibly not be harmful to plants (Primavesi, 2006).

As long as clay crystals are intact the possibility of exchangeable Al at toxic rates is low. However, when a soil is under anaerobic conditions due to its compaction and its pH value decreases or increases too much, clay undergoes a weathering process and aluminum release is increased (Primavesi, 2006). That is why soil management is important, to avoid soil compaction over crop cycles. Nevertheless, in soils under warm and moist climates, such as tropical conditions, bases (Ca^{2+} + Mg^{2+} + K^{+}) and silicate are quickly removed from the minerals, and the most simple clays (kaolinite) and iron and aluminum oxides remain. This intense and long weathering process releases Al^{3+}, ions, increasing the m% value of soils under tropical conditions.

Interpreting Al values (high, average, low) is useful (Table 7), but interpreting H + Al depends on CEC values, which vary among soils. Aluminum contents considered high in sandy soils may be minor in clay soils that generally have higher CEC values.

[11] 1:1 clay: two-layer mineral clay. It is structured in sheets composed of two layers of silicate tetrahedra and a central layer of aluminum octahedra. Examples: kaolinite and halloysite. These are clays with low surface charges (cation exchange capacity) and pH dependent. They are the most common ones in tropical soils.

Table 7. Interpretation of aluminum saturation values (m%) in the soil according to Osaki (1991).

m%	Classification
< 5	Very low (not harmful)
05–10	Low (somewhat harmful)
10.1–20	Average (moderately harmful)
20.1–45	High (harmful)
> 45	Very high (very harmful)

For a correct evaluation of aluminum toxicity, Al saturation (m%) must be calculated according to Equation 2.

Organic matter (OM) importance for soils under tropical conditions

Contrarily to soils under woodlands, agricultural soils under tropical conditions are predominantly populated by very active aerobic microorganisms, which makes humus accumulation hard. Targeted and periodic production of aggregate substances in intermediate phases of the complete OM decomposition[12] is, therefore, the only form of maintaining the productivity of these soils (Primavesi, 2006).

After some years of cultivation, OM contents in the soil become stable at around 25 to 30 g per dm^3 in clay soils and at lower values in soils of sandy or medium textures. Thus, when rich in OM, an agricultural soil is probably located in regions which are cold or of high altitudes, has excessive water content (O_2 deficiency) or is extremely poor in nutrients.

These three situations inhibit the plain activity of the microorganisms responsible for decomposition, and thus cause OM to accumulate.

[12] Soil organic matter (OM): every dead substance in the soil that comes from animal and vegetable residues at several decomposition stages. Plays an important role in the soil, improving its physical and chemical characteristics, and adding to it important physicochemical properties, such as cation exchange capacity.

Kaolinite and iron and aluminum oxides, which are important components in the mineral fraction of soils, may offer small contributions to cation exchange capacity, but OM may account for over 80% of the total CEC value. However, the negative charges in OM come from the dissociation of H+ ions from carboxyl and phenyl radicals and, therefore, are effective only under high pH values (when H^+ ions may be neutralized by hydroxyls).

A soil rich in OM features high total CEC values. However, if the soil is acid, it may feature low effective CEC values. If the conditions are favorable for the survival of bacteria and fungi, humic acids are formed. These acids play an important role in forming lumps and macropores which are responsible for making the soil soft and making it easier for air and water to enter the soil.

Organic matter is not an organic fertilizer in its essence, but rather a biophysical conditioner that recovers soil porosity. Also, because its density is lower than that of minerals, OM reduces the soil's apparent density[13].

When humified, OM yields more benefits, by increasing the soil's cation exchange capacity and its buffering capacity (important for substrates fertilized using chemicals).

Among the several organic substances available, only humus is capable of influencing soil chemical properties, although straw, during its decomposition, has a stronger influence on the soil's physical properties. Nevertheless, the effects produced by OM depend on its adequate management. Therefore, it must be applied to the surface, never buried.

The contribution of both OM and mineral fraction to the soil's CEC may be determined. Organic matter, even in significantly lower contents than the clay fraction, is the main responsible for CEC and contributes with 56% to 82% of the total negative electric charges (Table 8). These data highlight the importance of adequately managing OM when aiming to increase the soil's capacity to retain cations.

[13] Apparent density: the mass of dry soil by unit of apparent volume, i.e. the natural volume of the soil, including its pore space. Values higher than 1.4 kg/m³ usually indicate densification or compaction of the soil, except for clay soils.

Table 8. Cation exchange capacity (CEC) of soil samples, both total and in organic matter (OM). Adapted from Raij et al. (1996).

Soils	Depth (cm)	Clay content (g/kg)	OM content (g/kg)	CEC		
				TOTAL ($cmol_c/dm^3$)	OM ($cmol_c/dm^3$)	CEC % due to OM
A	0 – 65	50	8	3.2	2.2	69
B	0 – 15	60	6	3.3	2.1	64
C	0 – 14	120	25	10	8.2	82
D	0 – 16	190	24	7.4	6	81
E	0 – 12	130	14	3.7	2.7	73
F	0 – 15	640	45	24.4	15	62
G	0 – 18	590	45	28.9	16.1	56
H	0 –17	240	12	3.9	2.9	74

The most rational and ecological form of maintaining or increasing the fertility of tropical soils is by making frequent additions of OM during cultivation, even though this technique is often economically and technically impracticable in large areas. This is plainly feasible in small areas, and contrarily to what usually happens in tropical soils cultivated using traditional methods, over time the soils' physical, biological and chemical conditions improve significantly (Table 9).

Table 9. Organic matter influence on the chemical characteristics of a Ferralsol/ Oxisol (Latossolo) (A) in the city of São Carlos, São Paulo state, Brazil, and the same substrate after six years (B) of sequential crops of vegetables in a greenhouse and periodically fertilized using OM: ashes, cattle manure, sugarcane bagasse decomposed by inoculated fermentative microorganisms, wood sawdust and rice straw used as mulch.

Soil	P_{resin} (mg/dm^3)	OM (g/dm^3)	pH ($CaCl_2$)	K^+	Ca^{2+}	Mg^{2+}	H+Al	T= BS	CEC	V (%)
				($mmol_c/dm^3$)						
A	7	19	4.6	0.5	10	4	28	14	43	34
B	322	62	6.9	5.9	352	23	12	81	393	97

Soil fertility and productivity maintenance under tropical conditions

Soil fertility is only one among several factors that determine crop yield magnitude and interfere with agricultural productivity. Soil fertility may be a result of natural causes, or may be created by the addition of nutrients to the soil during crops. Even if fertile in its native state, a soil may, under inadequate management, be transformed to a low fertility soil.

Based on experiments performed by Liebig (1803–1873), soil fertility is now treated in terms of its nutrient stock and of the need to add chemical products, incorporating the main elements needed for the development of the plants.

A fertile soil contains sufficient and balanced amounts of all the nutrients needed by plants under assimilable form. This soil must be rather free of toxic materials, and its physical and chemical properties must supply the plants' demands. A fertile, productive soil must be located in a climatic zone which is able of providing enough humidity, nutrients and structure for the development of the plants and their roots.

Fertility losses are aggravated if a tropical soil is managed as if it were a temperate-climate soil poorer in nutrients and located in a region of warmer climate (Table 10). Plants react differently to tropical climate. Therefore, to yield high biomass production, they also demand that the soil is managed differently than soils under temperate climate.

Table 10. Physical and chemical characteristics of soils cultivated under tropical and temperate conditions. Adapted from Primavesi (2006).

TROPICAL Soil	TEMPERATE Soil
Deeper	Shallower
More weathered	Less weathered
Predominance of kaolinite	Predominance of montmorillonite and smectite
Exchange complex – 10 to 70 $mmol_c/dm^3$	Exchange complex – 500 to 2,200 $mmol_c/dm^3$

(to be continued...)

Table 10. (continued)

TROPICAL Soil	TEMPERATE Soil
Aggregation by oxidated Al^{3+} and Fe^{3+}	Aggregation by Ca^{2+}
Low mineral richness	High mineral richness
Soil correction at pH 5.6 – 5.8 CEC saturation from 25% to 40%	Soil correction at pH 6.8 – 7.0 CEC saturation up to 80%
Low cation exchange capacity (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+})	High cation exchange capacity (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+})
Poorer in silica and richer in aluminum and iron (oxides)	Richer in silica and less rich in iron and aluminum
Low adsorption of K and NH_4	High adsorption of K and NH_4
High P immobilization capacity	Low P immobilization capacity
Higher anion exchange capacity (SO_4^{2-} , PO_4^{2-}, NO_3^{-} , Cl^{-})	Lower anion exchange capacity (SO_4^{2-} , PO_4^{2-}, NO_3^{-} , Cl^{-})
More acid	Less acid
Friable	Sticky
More granulated structure in its native state	Less granulated structure
Quickly decomposes OM, rarely accumulates humus Fulvic acid leaches	Slowly decomposes OM, may accumulate humus and humin
Active microorganisms, needs limitation – minimum tillage 15 – 20 million active microorganisms per gram up to 15 cm Easily eroded by torrential rainfalls	Less active microorganisms, needs deep 'tillage' 2 million active microorganisms per gram up to 25 cm Rarely eroded, due to mild rainfalls
Heats up easily, needs protection from sunlight	Very cold, needs heating by direct sunlight
Optimum temperature 25 °C	Optimum temperature 12 °C
Soil must be protected from heat and rainfall impact	Clean soil to capture heat
Evaporation especially due to direct heating of soil	Water evaporation only by the plants
Low water retention capacity	High water retention capacity

Tropical soils are very poor in minerals when compared to temperate climate soils. However, tropical soils are deeper and richer in life forms, and display much higher amounts and diversity of microorganisms. The efficient and strong recycling of leaves and branches produced by vegetable biomass nurtures life in the soil. This life aggregates the soil, enabling air and water to enter into it and roots to expand, which under optimum rainfall conditions – such as in Amazônia, the Amazon biome –, creates conditions for the development of an exuberant and highly productive forest vegetation, maybe the largest of its kind in area in the world.

Some regions featuring annual rainfall rates around 2,300 mm, such as the Brazilian state of Amapá, display trees with heights that surpass 70 m – in 2019, a specimen of *Dinizia excelsa* (common name in Portuguese: *angelim-vermelho*) 90-m tall was discovered. Under adequate management, using technologies which are fit for tropical soils and which also benefit biodiversity, agricultural areas may yield productivity values similar to those of primary forests and their soils do not undergo a decay process; on the contrary, they recover.

Tropical soils are a different sort of ecosystem. They naturally feature very good aggregation, thanks to the richness of iron and aluminum sesquioxides and to the presence of OM. When cultivated, these soils lose OM and their CEC values drop as a result. Limestone application removes obstructions and releases new charges, which are occupied by Ca and Mg and other nutrients added by mineral fertilization. However, prolonged agricultural use, under which the soil is revolved and exposed to rain and sunlight, produces conditions which are favorable for OM degradation and consequently for the destruction of the soil's biostructure[14], thus drastically reducing its production potential.

Maintaining soil fertility under tropical conditions requires prioritizing the conservation of its biostructure, because such soils have more aggregates[15] (due to their sesquioxide richness), are more granulated and deeper than temperate soils. This last characteristic may make up for the low capacity of

[14] Biostructure: system of granulates and pores produced by microorganisms in the presence of organic matter and water.

[15] Aggregates: disposition of soil particles (sand, silt and clay) adhered in such a way that they behave mechanically as a single unit

replenishing the soil solution with nutrients in tropical soils. Their exchange complex is low and based in kaolinite clay 1:1, which has low exchange capacity. Temperate soils feature montmorillonite clays 2:1[16], with higher exchange capacity.

Thus, cultivation techniques to be employed in tropical soils must be different from those employed in temperate soils. Under tropical conditions, the adoption of conservation agriculture has shown potential for reversing chemical, physical and biological degradation processes in acid tropical soils. No tillage[17], for example, is a complete technique which aims to preserve the structure of the granulates in the soil surface. The main consequence of the adoption of the no-tillage system in comparison to conventional tillage is the increase in OM contents in the soil (due to the less oxidative environment and to less contact between vegetation residues and the soil), not revolving and protecting the soil's surface against impacts caused by rainfall and sunlight.

The adoption of the no-tillage system (*Sistema de Plantio Direto* - SPD) by Brazilian farmers from the 1970s on is considered a milestone in terms of conservation and preservation of soils in the country, which faced grave problems due to soil losses caused by erosion. Its adoption has been increasing exponentially, and SPD is currently practiced in approximately 35 million hectares over all Brazilian regions. The United States already use SPD in 35 million hectares of crops, Argentine uses it in 27 million hectares of crops, Australia, in 17 million hectares, and Canada, in 16 million hectares. All over the world, more than 100 million hectares of crops are cultivated using SPD.

No-tillage decreases agricultural production risks by increasing water use efficiency, especially during hot spells, making rainwater infiltration into the soil easier and its evaporation more difficult, due to the dead plant cover on the soil. Besides, not revolving the soil and maintaining the straw on its surface help reduce CO_2 emissions to the atmosphere, partially increases the OM

[16] Clay 2:1: three-layered clay. It is structured in sheets composed of two layers of silicate tetrahedra and a central layer of aluminum octahedra. Examples: montmorillonite, illite and vermiculite. Their surface charge is high and steady (does not depend on pH). Common in mildly weathered soils.

[17] No-tillage: a set of integrated techniques which aims to improve environmental conditions (water – soil – climate) to best explore the genetic production potential of crops. Has at least three minimum requirements – no revolving of the soil, crop rotation and use of cover crops for straw production –, and may be associated to the integrated management of pests, diseases and weeds.

contents and consequently sequesters carbon in the soil. Carbon stocks in the soil increased the most under the SPD system in comparison to the soils under native vegetation in the Brazilian Cerrado savannas (Table 11).

Table 11. Carbon stocks (C), accumulation rates and losses in the 1.0-m depth soil layer under Brazilian Cerrado savannas (and under other uses and land management forms. Adapted from Carvalho et al. (2010).

Use system	C stock in the soil (Mg*/ha)	Variation in comparison to native Brazilian Cerrado savanna		
		C stock in the soil (Mg/ha)	Time (Years)	Loss or accumulation rate (Mg/ha/year)
Brazilian Cerrado savanna	133	–	–	–
Eucalyptus	148	+15	12	+1.25
Sown pasture	150	+17	18	+0.94
Heavy disc harrow	125	-8	12	-0.67
Disc plow	128	-5	15	-0.33
No-tillage	155	+22	15	+1.47

*Mg (megagrams) (1 Mg = 10^6 g) = 1 ton.

Another important characteristic of the no-tillage system is the lesser use of agricultural machinery. In the conventional system, an inadequate or excessive use of implements pulverizes and destabilizes soil aggregates, increasing the temporary macroporosity in the mobilized layer and the compaction or densification of the soil immediately below this layer, due to the excessive traffic of machinery and equipment, which decreases root growth and hydraulic conductivity in this layer, thus increasing erosion risks.

Temporary macroporosity conveyed by conventional tillage is quickly lost, due to the accommodation of soil particles disaggregated by rainfall, decreasing gas exchanges (oxygen) and plant root growth.

Minimum tillage is another widespread technique in Brazilian tropical agriculture. It consists on minimum soil disturbance and is employed especially in crops that are planted in the same area over several years without any soil mobilization, such as semi-perennial crops, like sugarcane, or perennial crops, such as citrus and coffee, or even reforestations, such as eucalyptus crops.

Halfway between the conventional and no-tillage systems, minimum tillage makes minimum use of agricultural machinery, causing less mobilization, disaggregation and compaction, thus enabling better soil conservation.

Harmful effects of disaggregation and compaction reduce the soil's macroporosity and hydraulic conductivity, increases soil density and resistance to penetration; they also decrease profits, due to expenses with maintenance and fuel for agricultural machinery and implements.

Minimum tillage aims to decrease as much as possible the number of harrowings, plowings or rippings that mobilize and powder the soil, and replace these implements which are periodically used to prepare the soil by others which conserve the soil's structure by applying null or minimum tillage.

Some of these implements are better at preserving soil integrity, such as: the subsoiler, which is used for subsoiling before planting and which ruptures compacted soil layers, making it easier for the plants' roots to penetrate the soil, and water to infiltrate into deeper soil layers; trimmers, which cut, chop and minces the vegetation mass between crop lines, so that this dead biomass adds OM and increases soil humidity; equipment for the application of fertilizers and corrective dressings that do not mobilize the soil; as well as other less conventional ones, such as knife rollers, which chop the plant biomass over the soil.

The use of integration systems which incorporate agriculture, husbandry and forestry activities, whether in a spatial and/or temporal dimension, with the aim of producing synergic effects between these components has become another relevant form of sustainable tropical production over the last years.

Integration systems are expanding, especially in grain, wood and beef and milk cattle production, and are known as integrated crop-livestock-forest systems (ICLF). The use of these systems, when their adoption is possible, becomes of great importance for the recovery of degraded areas, both those used for pastures and those used for crops. Integrations may vary and encompass only integrated crop–livestock (ICL), livestock–forestry (ILF) or crop–forestry (ICF) systems.

These systems guarantee both diversification and the maintenance of the soil constantly vegetated, thus enabling erosion control and productivity increase, as well as reducing the pressure for the opening of new agricultural areas over natural areas. The introduction of ICLF systems conveys more efficiency to land use and produces further benefits to the soil and environment, such as:

- Greater erosion control, due to the increase in soil cover by the straw produced from residues of rotary crops and pastures.
- Improvement of microclimate conditions, a contribution of the trees to the system: reduction in temperature range, increase in relative humidity, decrease in wind intensity, and improvement in animal well-being, due to the greater thermal comfort.
- Increase in organic matter contents in the soil, from the litter and dead roots of trees, forages and crops, which stimulates the development and the biodiversity of the soil biota, improves soil porosity and consequently water infiltration.
- Recovery, especially through the roots of trees and forages, of nutrients leached or drained to deeper soil layers.
- Mitigation of the greenhouse effect by means of carbon sequestration, especially by the forest component.
- Diversification of production systems and consequent reduction in production costs, as well as decrease in risks involved in agriculture, especially those related to climate variations and market oscillation.

Aside from the benefits to the soil and environment, integration systems that encompass the tree component are able of adding value to the produced meat, because in such integration systems the methane (CH_4) emitted by the cattle may be neutralized by carbon accumulation (absorbed in the form of CO_2) in the biomass of the trees.

In 2020, Embrapa developed and launched the Carbon Neutral Brazilian Beef (CNBeef), which is depicted by a stamp indicating that the cattle is produced under integration systems. The CNBeef stamp is intended to attest that enteric methane emissions produced by these cattle were compensated for by trees grown during the production process. It is also intended for guaranteeing that the animals are reared in a thermally comfortable environment, under higher well-being standards, due to the shadow produced by the tree component. Estimates account for nearly 15 million hectares of areas equipped with some type of integration system in Brazil.

Soil fertility and geotechnologies

The spatial variability of the crops is mostly studied by means of samplings, which are often collected manually and laboriously, which ends up making these practices inoperative. Technologies currently under development aim to obtain vegetation indices collected by remote sensing, and to correlate them to chemical and physical attributes of the soil and biophysical parameters of the plants. The production factors that may spatially limit production are inferred using maps of soil productivity and soil attributes. These information enable managing specific places (management zones) according to their characteristics (topography, soil compaction, electrical conductivity, water availability, fertility, etc.) and potentially obtaining profitability increases and reducing environmental impacts by means of more targeted fertilizer and pesticide applications, irrigation and planting in accordance with each region's potential.

References

BERGMANN, W. **Plant diagnosis and plant analysis**. Jena: VEB Fischer, 1973.

CARVALHO, J. L. N.; AVANZI, J. C.; SILVA, M. L. N.; MELO, C. R. de CERRI, C. E. P. Potencial de sequestro de carbono em diferentes biomas do Brasil. **Revista Brasileira de Ciência do Solo**, v. 34, n. 2, p. 277-290, 2010.

FAO. **The future of food and agriculture: trends and challenges**. FAO, 2017. Available in: http://www.fao.org/3/a-i6583e.pdf. Accessed on: 07 maio 2020.

LARCHER, W. **Physiological plant ecology**: ecophysiology and stress physiology of functional groups. 4. ed. New York: Springer, 2004. 513 p.

LIEBIG, J. von. **The natural laws of husbandry**. New York: Arno Press, 1972. 387 p. Reprinted, first published in 1863.

MALAVOLTA, E.; VITTI, G. C.; OLIVEIRA, S. A. **Avaliação do estado nutricional de plantas**. Piracicaba: POTAFOS, 1989. 201 p.

MELLO, F. de A.; BRASIL SOBRINHO, M. de O. C.; ARZOLLA, S.; SILVEIRA, R. I.; COBRA NETO, A.; KIEHL, J. de C. **Fertilidade do solo**. São Paulo: Nobel, 1983. 400 p.

OSAKI, F. **Calagem e adubação**. Campinas: Instituto Brasileiro de Ensino Agrícola, 1991. 503 p.

POTASH & PHOSPHATE INSTITUTE (Atlanta, Ga.). **International Soil Fertility Manual**. Atlanta, GA: Potash & Phosphate Institute, 1995.

PRIMAVESI, A. **Manejo ecológico do solo**: a agricultura em regiões tropicais. 18. ed. São Paulo: Nobel, 2006. 549 p.

RAIJ, B. van; CANTARELLA, H.; QUAGGIO, J. A.; FURLANI, A. M. C. **Recomendações de adubação e calagem para o Estado de São Paulo**. 2. ed. Campinas: Instituto Agronômico de Campinas, 1996. 285 p. (IAC. Boletim Técnico, 100).

TOMÉ JÚNIOR, J. B. **Manual para interpretação de análise de solo**. Guaíba: Agropecuária, 1997. 274 p.

Embrapa
Territorial

MINISTRY OF
AGRICULTURE, LIVESTOCK
AND FOOD SUPPLY

PÁTRIA AMADA
BRASIL
BRAZILIAN GOVERNMENT