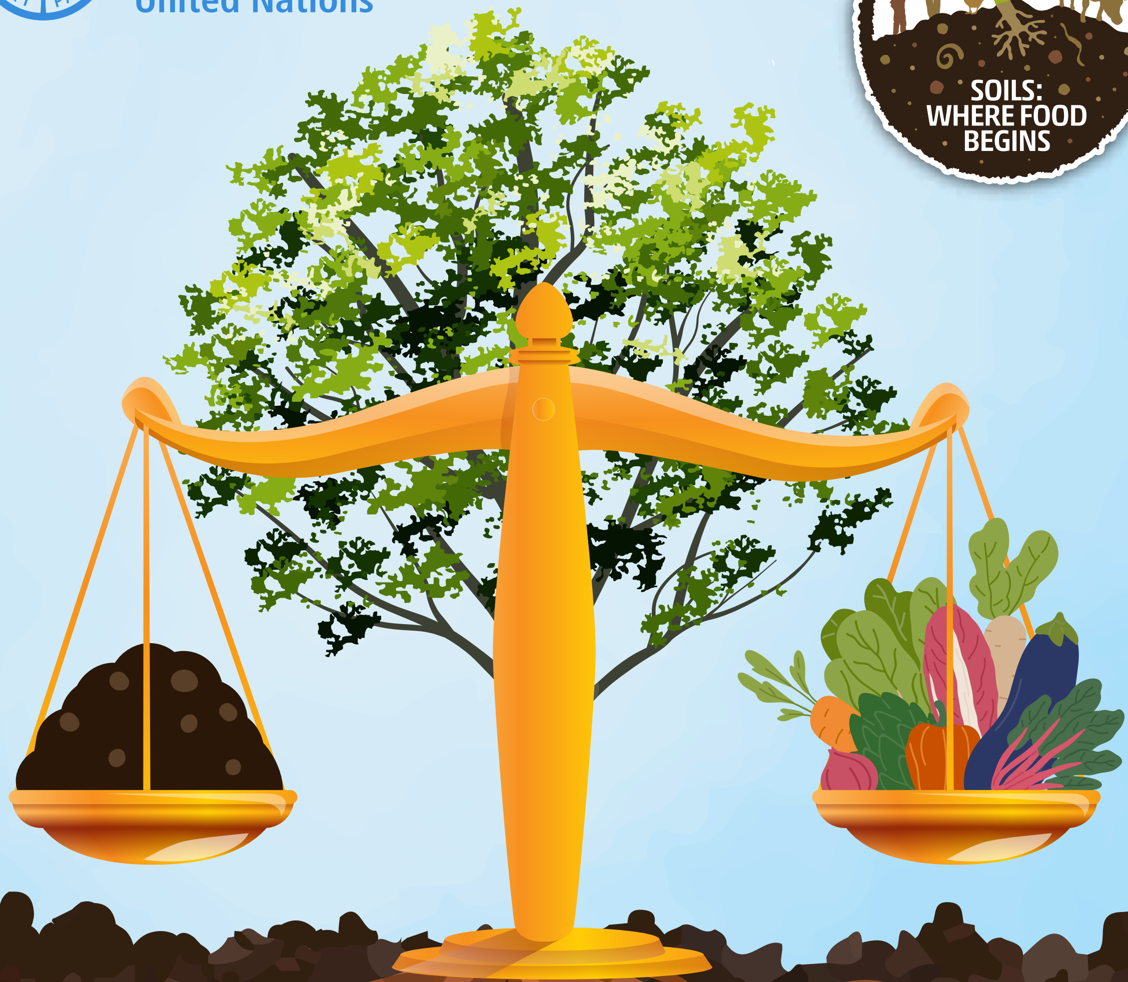
Food and Agriculture Organization of the United Nations

SOILS: WHERE FOOD BEGINS



Soils for nutrition: state of the art

GLOBAL SOIL PARTNERSHIP

Soils for nutrition: state of the art

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Food and Agriculture Organization of the United Nations
Rome, 2022

Required citation:
FAO, 2022. *Soils for nutrition: state of the art*. Rome.
https://doi.org/10.4060/cc0900en

ISBN 978-92-5-136610-3

Cover design: Matteo Sala

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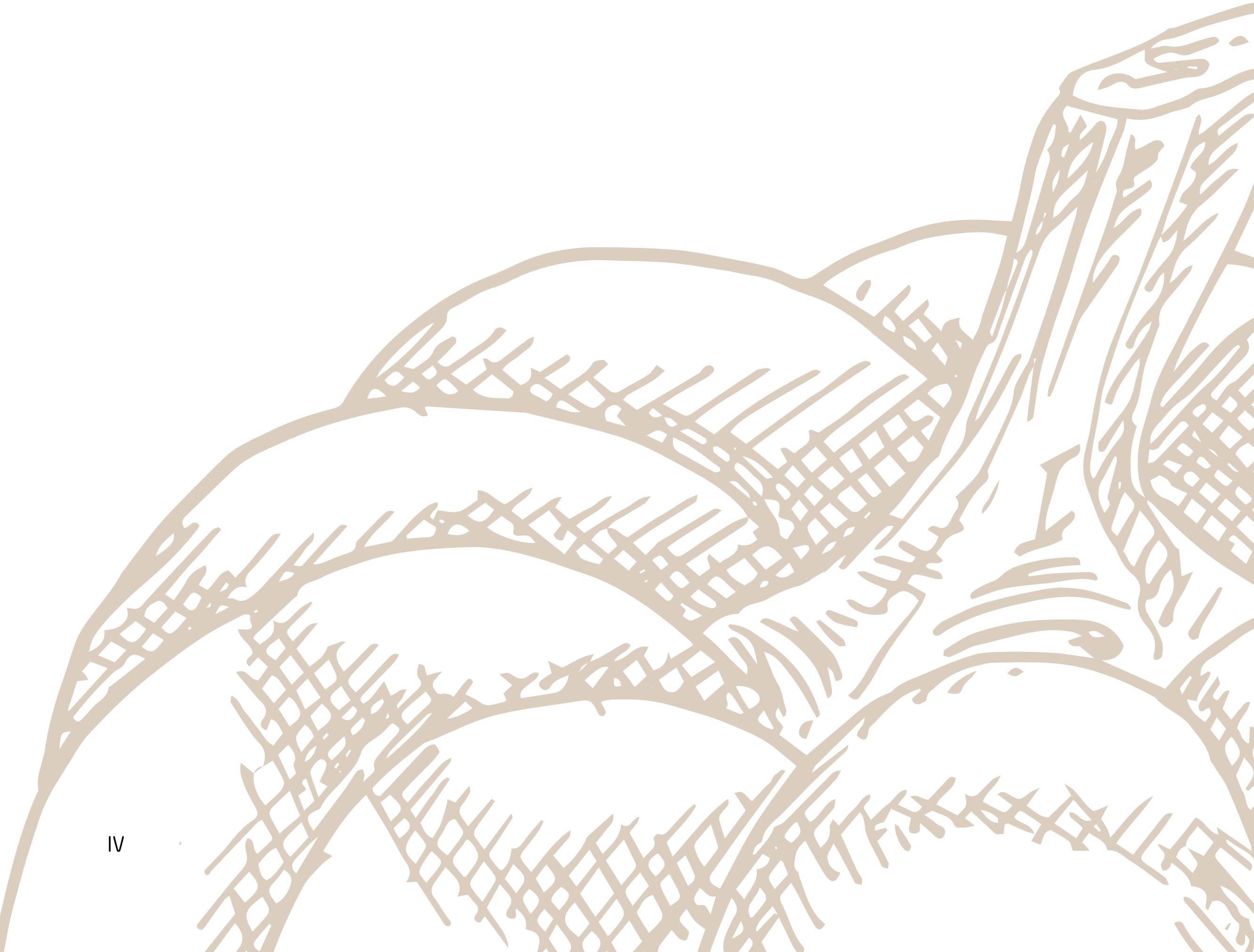

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Preface

Soils are fundamental to life on earth, and the ability of soils to provide safe and nutritious food is a key contribution they make to us and to nature as a whole. About 95 percent of our food nutrients come from soils, which have a natural capacity to provide nutrients to support crop growth. Globally, however, not all soils have the same ability to provide nutrients. Currently we are facing a contrasting scenario of nutrient imbalances. In some regions, soils are naturally unfertile with little or no agricultural capability; in other regions, soil degradation has reduced fertility. In both situations, crop growth is reduced due to a lack of nutrients in the soil. On the other hand, there are soils in which excessive additions of nutrients through improper management has led to the soil, air, and water pollution and serious terrestrial and aquatic biodiversity effects. These highly contrasting nutrient imbalance scenarios both contribute to food insecurity and are not environmentally or economically sustainable or socially fair; both also lead us down a path that exacerbates global climate change and greenhouse gas emissions.

The overarching goal of the United Nations is sustainable development via the achievement of the Sustainable Development Goals (SDGs). As part of this global program, the Global Soil Partnership (GSP) was established to develop a robust interactive partnership and enhanced collaboration and synergy of efforts between all stakeholders for sustainable soil management (SSM). Ten years after its creation, the GSP has developed critical documents for the conservation and improvement of the world's soils, including the Status of the World's Soil Resources (SWSR) report, the Voluntary Guidelines for Sustainable Soil Management (VGSSM), and the International Code of Conduct for the Sustainable Use and Management of Fertilizers (Fertilizer Code), which have been milestones in the protection of soils and their positioning on the global agenda. The SWSR reported on the ten main threats to soil health, including erosion, soil organic carbon loss, nutrient imbalances, salinization, and acidification, and the VGSSM outlined key actions to counteract and reverse these soil degradation drivers. In both documents nutrient imbalance was identified as a major threat affecting soil health globally (FAO, 2015), leading to devastating environmental, social, and economic effects. Even though 195 million tonnes of fertilizers were applied in 2020, with an annual application rate increasing every year, hunger still affected 768 million people (FAO, 2019b).

Nutrient imbalance is a significant obstacle on the road to food security as it directly affects food production, quality, and safety. One of the main dimensions of food security is sufficient food production, which can be supported by improving soil fertility. Soil fertility is the ability of soil to support plant growth by providing the essential nutrients and adequate chemical, physical, and biological conditions as a habitat for plant growth and the maintenance of ecosystem services (FAO, 2015). The lack of essential nutrients, including macro and micronutrients, leads to the underdevelopment of plants and a decrease in yield and in crop nutritional value.

Efforts and investments focused on increasing plant nutrient uptake and balance, and ultimately, human and animal nutrition can be lost if soils are not healthy. When soils are compacted, eroded, have their nutrient and soil organic matter (SOM) depleted, or have chemical toxicity issues due to contamination by pollutants, acids, or salts, they cannot produce food that contains the nutrients necessary for human health or even assimilate nutrients added by fertilizers application. While the need to increase food production for an increasing population is unquestionable, the focus should be not only on producing more food but also on producing better food. Sustainable soil management (SSM) is essential to preserve and increase nutrient content in soils, plants, animals and humans. The use of nutrient-rich varieties of staple crops, in conjunction with soil health, represents a technological advance for reducing malnutrition, especially if the staple crops are grown with, or in rotation with, other species like native species or legumes, which encourage dietary diversity and improve nutrient cycling and biodiversity.

Nutrient imbalance is also a significant driver of environmental degradation and greenhouse gas emissions. Although adding fertilizers represents indisputable benefits for agricultural production, and their proper use may contribute to increased SOM and soil health, misuse and overuse of fertilizers increase global climate change, degradation of soil and water resources, and harm human, animal and soil health. A growing concern associated with using some mineral fertilizers and recycled nutrient sources is their quality and safety. Harmful microbes and heavy metal content may be a cause of severe and persistent environmental pollution and induce significant human health problems. Maintaining soil fertility should not be responsible for environmental pollution from fertilizer extraction and processing. In addition, mineral reserves depletion derived from mining for fertilizer production highlights the urgency of using soil nutrients efficiently, safely and sustainably.

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Acronyms and abbreviations

AMB	Arbuscular mycorrhizal fungi
BNF	Biological nitrogen fixation
CPFP	Combined Phytoremediation and Food Production
EEF	Enhanced Efficiency Fertilizers
Fertilizer Code	International Code of Conduct for the Sustainable Use and Management of Fertilizers
FUE	Fertilizers use efficiency
GHG	Greenhouse gas
GSP	Global Soil Partnership
IoT	Internet of things
IPCC	Intergovernmental Panel on Climate Change
ISFM	Integrated soil fertility management
MIRS	Mid-infrared spectroscopy
MSW	Municipal solid waste
NbS	Nature Based Solutions
NDVI	Normalized Difference Vegetation Index
NF	N_2 fixing
Nr	Reactive nitrogen
NUE	Nitrogen use efficiency
POP	Persistent organic pollutants
PSS	Proximal soil sensing
SDG	Sustainable Development Goals

SOM	Soil organic matter
SSA	Sub Saharan Africa
SSM	Sustainable soil management
SWSR	Status of the World's Soil Resources
USDA	United States Department of Agriculture
VGSSM	Voluntary Guidelines for Sustainable Soil Management
vis-NIRS	Visible and near-infrared spectroscopy´
VRNF	Variable Rate Nitrogen Fertilization
WHO	World Health Organization

Chemical formulae and elements

Al	Aluminum
B	Boron
C	Carbon
Ca	Calcium
Cd	Cadmium
CO_2	Carbon dioxide
Fe	Iron
H	Hydrogen
Hg	Mercury
HNO_3	Nitric acid
I	Iodine

K	Potassium
Mn	Manganese
Mg	Magnesium
Mo	Molybdenum
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
Na	Sodium
NH_3	Ammonia
NH_4^+	Ammonium
NO_2	Nitrogen dioxide
NO_2^-	Nitrites
NO_3^-	Nitrates
NO_x	Nitrogen oxides
O_2	Oxygen
P	Phosphorus
Pb	Lead
S	Sulfur
Se	Selenium
Si	Silicon
Ti	Titanium
Zn	Zinc

Introduction

Food starts with soils, and as the target date to accomplish the SDGs grows closer, it is more urgent than ever to reverse soil degradation and tackle its effects on agrifood systems. *Soils for Nutrition: state of the art* addresses the contribution of healthy soils to the achievement of SDG 2 (Zero hunger), SDG 3 (Good health and well-being), SDG 6 (Clean water and sanitation), SDG-12 (Responsible production and consumption), SDG 13 (Climate action),and SDG- 15 (Life on land). Clearly, soils hold an enormous potential to provide a healthy environment that sustains the production of food, fodder, energy (biomass), fiber and meets life basic needs.

In pursuing our intensive production of food, we may be threatening our health and that of many other species on the planet, harming the environment and worsening the already difficult global scenario of environmental degradation, poverty, malnutrition, migration, disease, and climate change. Is it possible to unlock the productive potential of soils naturally and sustainably to obtain sufficient, nutritious, and safe food? Or do we rely exclusively on external inputs to replace mined soil nutrients and at what environmental and socioeconomic cost? This booklet attempts to answer these questions.

This booklet aims to review the role of soil fertility in producing sufficient, safe, and more nourishing food for healthier plants, animals, and people.

Soil fertility and nutrition involve processes at scales ranging from molecules to the entire planet. Our interventions in these processes may exacerbate the global challenges we face but can also be modified to solve them. This booklet contributes to understanding processes related to soil fertility from the perspectives of food production and food security, and the environmental and climate change impacts associated with fertilizer misuse and overuse. Finally, this booklet outlines the main areas of opportunity and the way forward to solve the nutrient imbalance prevailing in our current agrifood systems.

1. Status and trends of global soil nutrient budget

Malnutrition and food insecurity are long-standing problems for humanity. When discussing solutions and strategies to combat these problems, plant-based alternatives such as biofortification and improved crop varieties are frequently considered. However, the connection of soil with nutrient deficiencies in crops, food and humans is generally not so conspicuous. This lack of connection is perplexing since the primary source of the nutrients we all need to thrive are in soils. Plants acquire vital resources from two entirely different environments—the air and the soil. The nutrients we find in animal foods come from plants or plant-based foods, which obtain their nutrients from soils. Therefore, the nutritional quality of foods is directly related to the quality and health of soils. Healthy soils can sustain the productivity, diversity and environmental services of terrestrial ecosystems (FAO, 2020). If soils are not healthy, their ability to produce healthy and nutritious food is reduced or lost. Soils are complex ecosystems that perform the astonishing functions of originating, storing, transforming and recycling the essential elements that we all need and which are transferred from the soil to plants and then to animals. This storage and transfer of nutrients is possible through the intricate physical, chemical and biological processes involved in the transformation of inaccessible sources of nutrients such as nitrogen and phosphorus into plant-available forms. Soils are not inert: they are living ecosystems that provide the physical structure and support, and the chemical and biological environment for nutrient flow to the roots, affecting the mechanisms and amount for crop nutrient uptake and the regulation of nutrient leakage to the surrounding environment (Peoples *et al.*, 2014).

For the performance of all these functions, it is necessary to understand, value, and conserve the processes of soils that make possible the production of our food and its nutritional value, on which our health depends.

1.1. Soils as a source of nutrients

Soil fertility is the ability of a soil to sustain plant growth by providing essential plant nutrients and favorable chemical, physical and biological characteristics as a habitat for plant growth (Figure 1) (FAO, 2019c). Plants require essential nutrients to complete their life cycle (Hodges, 2010).

Integral concept of soil fertility

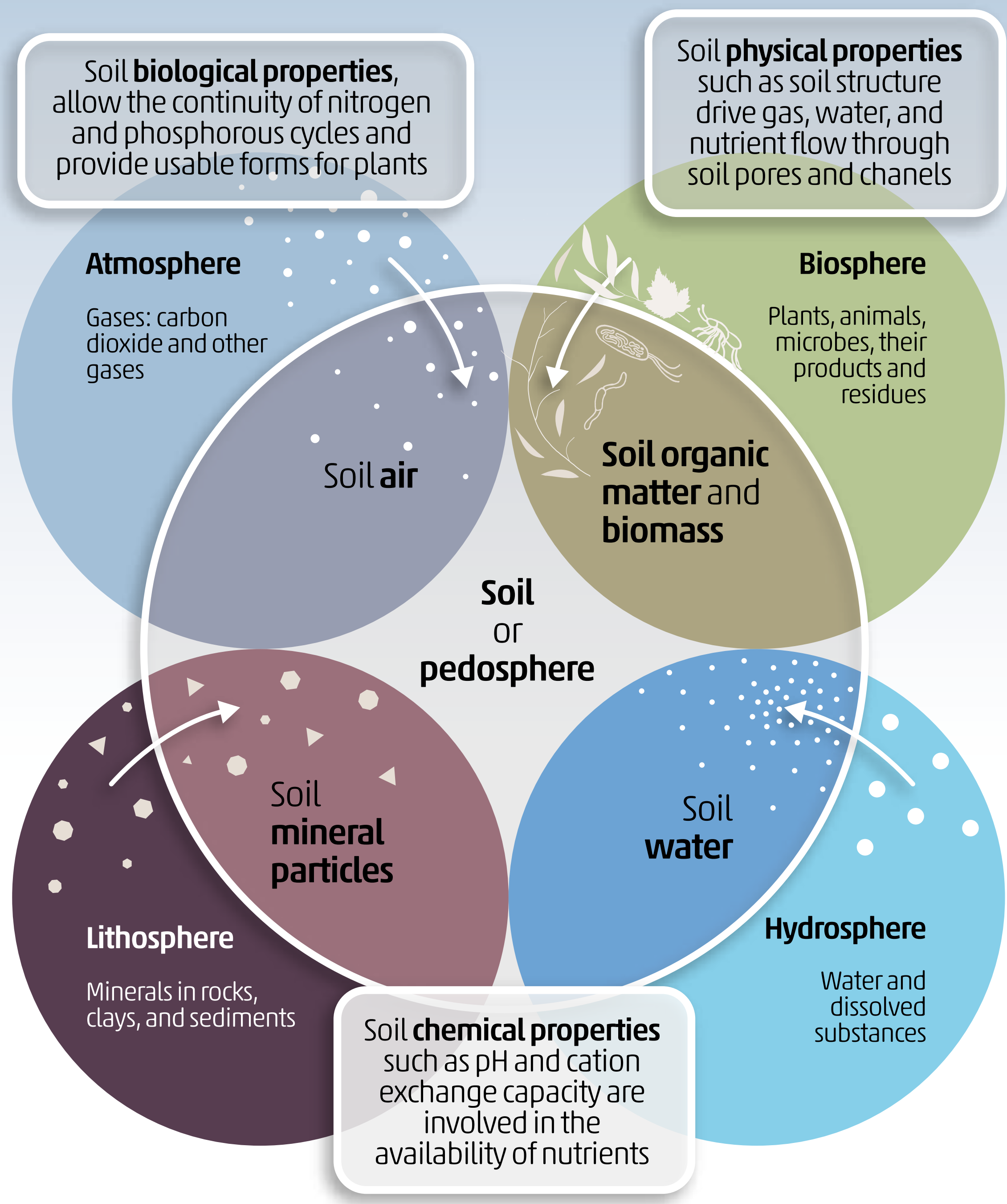


Figure 1. The integral concept of soil fertility encompasses physical, chemical, and biological properties, as well as the confluence of soil components including water, air, minerals, and biota. The interaction between soil properties and the different soil elements (mineral, water, air, and biota) make possible the continuity of relevant processes affecting directly or indirectly the nutrient availability for plants. The figure shows some examples of those processes

Source: Adapted from Weil, R.R. & Brady, N.C. 2017. The nature and properties of soils (global edition). *Harlow: Pearson*

Nutrients required in large amounts by plants (i.e. nitrogen (N), phosphorus (P), and potassium (K)) are classified as macronutrients. Elements such as iron (Fe), manganese (Mn), and zinc (Zn) are required in lesser quantities, and they are called micronutrients (Table 1). The solid soil phase (Figure 1) is the main nutrient reservoir of essential nutrients. The soil supplies 15 mineral elements required for the nutrition of higher plants, which are taken up by plants only in mineral form from the soil solution; the elements are made available from SOM mineralization, biological cycles, chemical and physical processes, or can be added as fertilizers.

Table 1. Essential nutrients used by plants, and their concentration in plant tissue

Source: Adapted from Hodges, S.C. 2010. Soil fertility Basics. NC Certified Crop Advisor Training. Chapter 1. Bassic Concepts. Soil Science Extension. North Carolina State University. http://www2.mans.edu.eg/projects/heepf/ilppp/cources/12/pdf%20course/38/Nutrient%20Management%20for%20CCA.pdf; Jones Jr., J.B. 2012. Plant nutrition and soil fertility manual. Second edition. New York, CRC Press. 230 pp. https://doi.org/10.1201/b1157.

Major nutrients			
Element	Symbol	Primary forms used by plants	Plant content (%, range percentage)
Nitrogen	N	NH_4^+, NO_3^-	0.5 - 5
Phosphorus	P	HPO_4^{2-} , H_2PO^{4-}	0.1 - 5
Potassium	K	K^+	0.5 - 5
Calcium	Ca	Ca^{2+}	0.05 - 5
Magnesium	Mg	Mg^{2+}	0.1 - 1
Sulphur	S	SO_4^{2-}	0.05 – 0.5
Micronutrients			
			ppm
Iron	Fe	Fe^{3+}, Fe^{2+}	50 – 1,000
Manganese	Mn	Mn, Mn^{2+}	20 - 200
Zinc	Zn	Zn^{2+}	10 - 100
Copper	Cu	Cu^{2+}	2 - 20
Boron	B	H_3BO_3 (Boric acid)	2 - 100
Molybdenum	Mo	Mo, MnO_4^{2-}	0.1 - 10
Chlorine	Cl	Cl^-	100 – 10,000

The availability of macro and micronutrients must be balanced and continuous for the correct metabolic functioning of crops. Justus von Liebig and Carl Sprengel established the "*the law of the minimum*" in 1840 which states that *"plant production can be no greater than that level* *allowed by the growth factor present in the lowest amount relative to the optimum amount for that factor*". If any of the essential elements is not supplied, it will limit plant growth, which may stop completely in absence of essential nutrients.

It is important that plant nutrients are present at adequate levels, but they should be also in bioavailable forms. Bioavailability (defined as the fraction of absorbed and utilized micronutrients, Davidsson and Tanumihardjo, 2012) depends on an adequate supply of these nutrients in the forms that can be absorbed by plants. For example, plants can only take up N in the form of nitrates (NO_3^-) and ammonium (NH_4^+) and this process occurs by mass flow. In contrast potassium can only be adsorbed by plants in the cationic (positively charged) form of K^+ through diffusion (Bertsch, 1995). For more examples about the absorption form of different soil nutrients see Table 2. Furthermore, a soil may have a good nutrient supply, but if its physical condition (e.g. compaction, waterlogging, etc.) or biological properties (soil biodiversity, biological cycles) is poor, the available nutrients cannot be used. That is why the concept of soil fertility requires a definition in a broad sense, which includes the chemical, physical and microbiological aspects that determine adequate plant nutrition.

Of the 18 essential elements that plants require for their growth, 15 of them are provided by the soil. The other three are carbon (C), hydrogen (H) and oxygen (O), which are taken up by plants from the atmosphere during the photosynthesis process (Hodge, 2010; Jones, 2012).

Table 2. Mobility in the plant, form of adsorption, and mechanism of mobilization from soils to roots of different soil nutrients.

Source: from Bertsch, F. 1995. La fertilidad del suelo y su manejo San José Costa Rica. Asociación Costarricense de la Ciencia de Suelo (ACCS): 43-117; Hodges, S.C. 2010. Soil fertility Basics. NC Certified Crop Advisor Training. Chapter 1. Bassic Concepts. Soil Science Extension. North Carolina State University. http://www2.mans.edu.eg/projects/heepf/ilppp/cources/12/pdf%20course/38/Nutrient%20Management%20for%20CCA.pdf; Jones Jr., J.B. 2012. Plant nutrition and soil fertility manual. Second edition. New York, CRC Press. 230 pp. https://doi.org/10.1201/b1157.

Nutrient	Adsorption form	Metabolic form	Mobility in the plant	Mobilization soil to roots
N	NO_3^-	NH_4^+	++	Mass flow
	NH_4^+	NH_3		
	Urea	NH_2OH^-		
	Amidas			
	Aminoacids			
P	$H_2PO_4^-$	$H_2PO_4^-$	+	Diffusion
	HPO_4^{-2}	HPO_4^{-2}		
		PO_4^{-3}		
K	K^+	K^+	++	Diffusion
Ca	Ca^{++}	Ca^{++}		Interception
				Mass flow

Mg	Mg^{++}	Mg^{++}		Interception Mass flow
S	SO_4^{-2}	S-H/S-S	±	Mass flow
Mn	Mn^{++} Chelates	Mn^{++}	±	Mass flow Interception
Zn	Zn^{++} Chelates	Zn^{++}	±	Mass flow Interception
Cu	Cu^{++} CuOH CuCl Chelates	Cu^{++}	-	Mass flow
Fe	Fe^{++} Fe^{+++} Chelates	Fe^{++}	-	Mass flow
B	H_3BO_3 $H_2BO_3^-$ HBO_3^{-2} BO_3^{-3} $B(OH)_4^-$ $B_4O_7^{-2}$		±	Mass flow
Mo	MoO_4^{-2} $HMoO^{4-}$		+	Mass flow
Cl	Cl^-		+	Mass flow

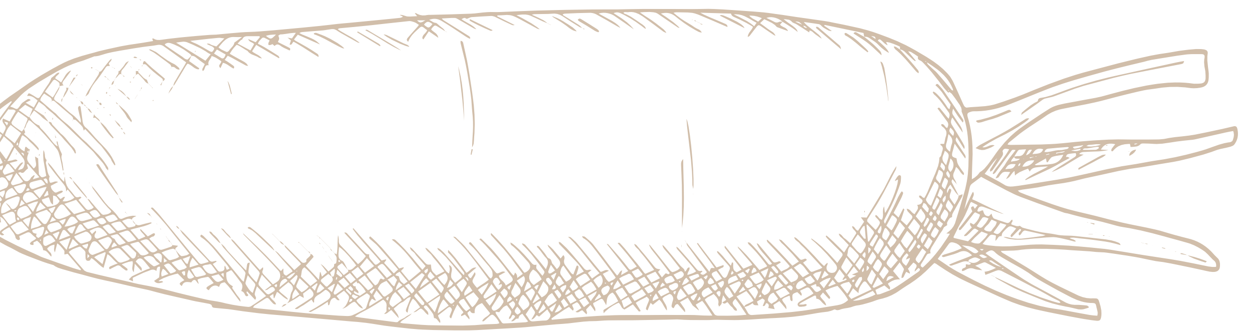
The global cycles of N, P, and K are depicted in Figures 2, 3 and 4. The Figure 2 shows the global N cycling indicating approximate magnitudes of the major pools (boxes) and fluxes (arrows). Nitrogen cycling takes place integrally in the atmosphere, soil, microbes and plants. The atmosphere contains most of the Earth's N. Although we may not realize it, we find ourselves surrounded and immersed in a cloud of N, in the form of dinitrogen (N_2), a stable gaseous N form which accounts for approximately 78 percent of the atmosphere volume (Erisman *et al.*, 2008). However, 99 percent of this N cannot be used by 99 percent of life forms of the planet, since it is an extremely stable chemical form or non-reactive form (Galloway *et al.*, 2003). Only through certain natural processes such as lightning and N fixation by microbes in which soil biodiversity plays a key role, N_2 can be transformed into reactive N (Nr), which refers to those forms of N capable of combining with other chemical forms in the environment (Galloway *et al.*, 2003). The Nr includes reduced form such as ammonia (NH_3) and NH_4^+, inorganic N in oxidized states like NO_3^-, nitric acid (HNO_3), N oxides (NOx), nitrous oxide (N_2O), and the N present in organic forms like proteins and nucleic acids (Groffman and Rossi-Marshall, 2013). The main reactive and non-reactive forms and processes of N cycling are summarized in the Table 3.

Table 3. The main forms and processes occurring in the N cycling in terrestrial ecosystems.
Source: Adapted from Groffman, P.M. and Rosi-Marshall, E.J. 2013. Chapter 7: The Nitrogen Cycle. In: K.C. Weathers, D.L. Strayer & G.E. Likens, eds. Fundamentals of Ecosystem Science. pp. 137–158. Academic Press. https://doi.org/10.1016/B978-0-08-091680-4.00007-X.

Pools/ Chemical Forms	Reactive/Nonreactive	Importance
Gases		
N_2	Dinitrogen (non-reactive)	Main global reserve, 79% of atmosphere.
N_2O	Nitrous oxide (reactive)	GHG gas, with a global warming potential of 298, destroys stratospheric ozone.
NO	Nitric oxide (reactive)	Toxic, precursor of tropospheric ozone
NH_3	Ammonia (reactive)	Plant available (soluble), can be toxic, rapidly deposited
NO_y	Atmospheric N produced by combustion of fossil fuels and/or atmospheric chemical reactions (reactive)	Plant available (soluble), component of acid rain, rapidly deposited
Ions/Soluble Forms		
NH_4^+	Ammonium (reactive)	Available to plants
NO_2^-	Nitrite (reactive)	Toxic, rarely found at high levels in nature, precursor of NO_3^-
NO_3^-	Nitrate (reactive)	Available to plants, highly leachable.
DON	Dissolved organic nitrogen (reactive)	Mixture of many different chemical forms.

Processes		
N_2 NH_3	Biological N fixation	Main natural N input
N_2 NO_y	Abiotic N fixation	N input
Organic N NH_4^+	Mineralization	Influences the availability of nutrients
NH_4^+ or NO_3^- Organic N	Immobilization	Influences the availability of nutrients
NH_4^+ NO_2^- NO_3^-	Nitrification	Influences N availability, denitrification processes, and N losses by leaching
NO_3^- NO_2^- NO N_2O N_2	Denitrification	The main nitrogen outflow pathway
NO_3^- NH_3	Dissimilatory nitrate reduction to ammonia (DNRA)	
$NH_4^+ + NO_2^-$ N_2	Anaerobic oxidation of ammonium (anammox)	

Under natural conditions, N fixation is the main N input pathway to terrestrial ecosystems. The highest rates of N fixation, typically 5 to 20 gm²/yr have been observed in legumes and other organisms with symbiotic capacity to fix N (Chapin, Matson and Mooney, 2002). Nitrogen input flows are enhanced by anthropogenic activities mainly through fertilizer production and application, combustion of fossil fuels and by planting N-fixing crops (Galloway *et al.*, 2003). Denitrification, defined as the biochemical reduction of NO_3^- or nitrite (NO_2^-) to gaseous N, either as N_2 or as NOx, is the main N outflow accounting for more than 60 percent (Chapin, Matson and Mooney, 2002) of the N outputs (Figure 2). The large size of the soil organic N pool (2 000 - 6 000 kg N/ha in organic matter (Powlson, 1993) reflects soil type and management, being greatest in soils containing clay which can stabilize SOM. Some fractions of SOM are very stable, with turnover times reaching hundreds or even thousands of years (Horward, 2015). Other SOM fractions, including plant or animal residues, are easily broken down by microorganisms producing carbon dioxide (CO_2) and inorganic N over periods of days or weeks (Horward, 2015).



The terrestrial nitrogen cycle

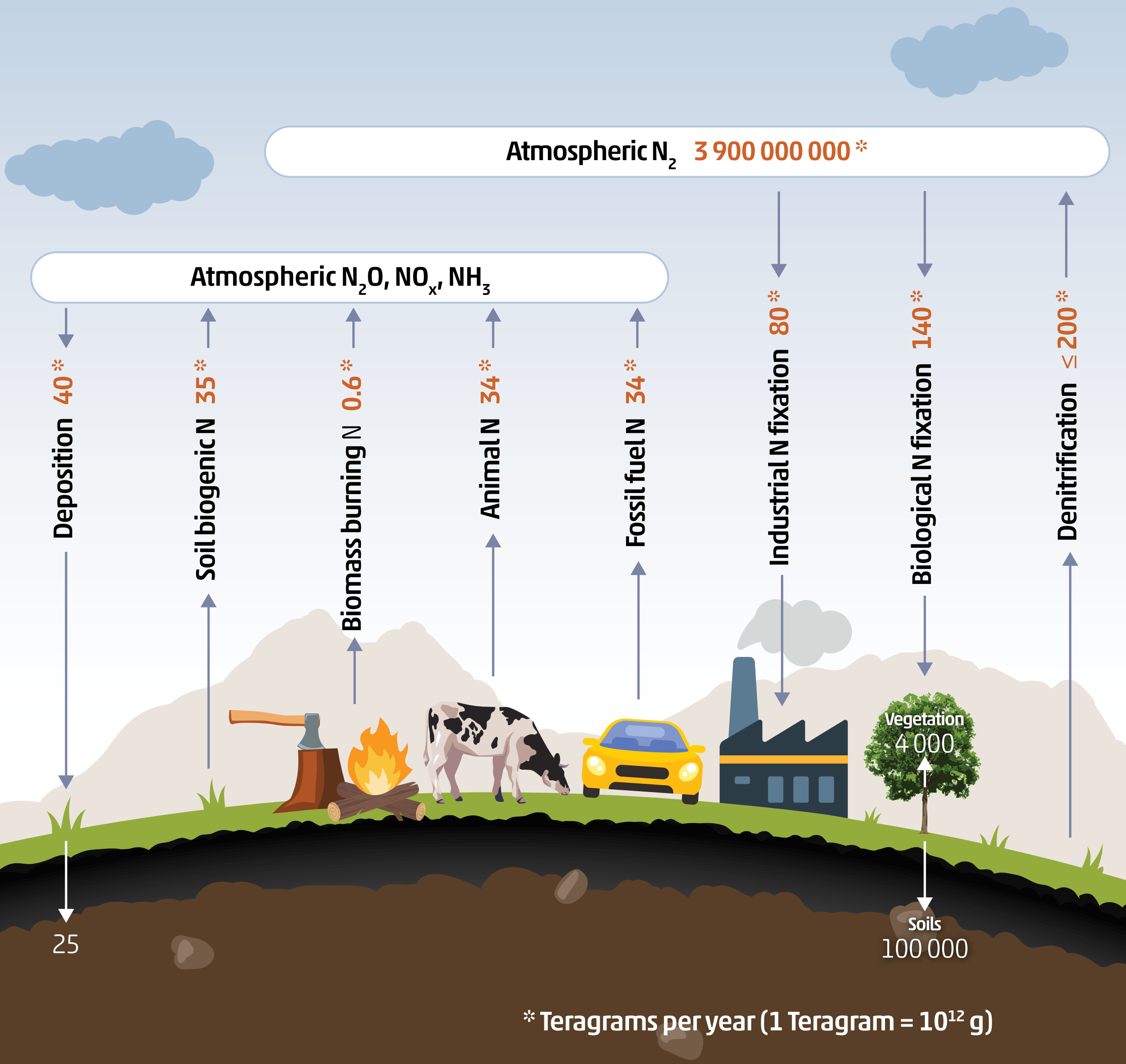


Figure 2. Global N inputs, outputs, and reserves occurring in the global circulation of N in terrestrial ecosystems. Units are Teragrams per year (1 Teragram = 10^{12} g)
Source: Adapted from Chapin, S. F., Matson, P. A., and Mooney, H. A. 2002. Principles of terrestrial ecosystem ecology. "http://dx.doi.org/10.1007/978-1-4419-9504-9"10.1007/978-1-4419-9504-9 Tian, H., Xu, R., Canadell, J.G., Thompson, R.L., Winiwarter, W., Suntharalingam, P., Davidson, E.A. *et al.* 2020. A comprehensive quantification of global nitrous oxide sources and sinks. Nature, 586(7828): 248–256. https://doi.org/10.1038/s41586-020-2780-0

Plants take up N mainly in the form of NO_3^-, which are formed in the soil by the process of nitrification, involving the transformation of NH_4^+ to NO_2^-, followed by its transformation to NO_3^- (Robertson and Groffman, 2015). Nitrate N is distributed in the soil pore space and the soil solution. However, not all the pore space is colonized by roots, so that NO_3^- that is not adsorbed by plant roots or utilized by soil microorganisms can be transported from the surface part of the soil to deeper parts by leaching (Robertson and Groffman, 2015), or it can be lost in gaseous forms such as N_2O or NH_3. Leaching involves the removal and transport of materials in solution in percolation water, in this case NO_3^- (Weil and Brady, 2017). Due to its negative charge, N in the form of NO_3^- is much more mobile compared with the NH_4^+ form. Soil mineral particles often have negative charge which attract positively charged NH_4^+ ions (Groffman and Rossi-Marshall, 2013). For this reason, the nitrification process is one of the factors controlling hydrological N losses and is an important pathway for N outflow. Another important pathway of N outflow is denitrification which refers to the biochemical reduction of NO_3^- or NO_2^- to gaseous N, either as N_2 or as an NOx such as N_2O. Nitrous oxide is produced in cropped soils by different microbial-mediated processes, but most is produced during the denitrification process. Denitrification is an important process especially in heavily fertilized or manured agricultural soils and rice paddies (Weil and Brady, 2017). Nitrification and denitrification reactions are driven by several factors such as soil temperature, water filled pore space, and the availability of mineral N and soluble carbon (Zhang and Liu, 2018). Ammonium volatilization to the gaseous form of NH_3 represents gaseous losses of N, which can occur during the decomposition of organic plant and animal wastes, excrement, and by the addition of fertilizers in the form of NH_3 and urea. Volatilization of NH_4^+ is more pronounced under certain conditions including elevated soil pH, high temperatures, soil desiccation, and in sandy, calcareous soils (Weil and Brady, 2017).

Phosphorus is present in small amounts in the Earth's crust and is rarely found in highly concentrated forms (Weil and Brady, 2017). It is an element that becomes available mainly through weathering of primary soil minerals such as apatite (Figure 3). For this reason, P is a scarce and limiting nutrient for the growth and production of terrestrial ecosystems (Elser *et al.*, 2007) and needs to be added as fertilizer or biofertilizer to some cultivated soils. The most frequent forms of P found in soils are phosphates including PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$, and $H_3PO_4^-$ so that P exists almost exclusively in its oxidized form as PO_4^- either in its inorganic, organic, dissolved or particulate form (Weil and Brady, 2017).

One of the greatest challenges regarding the agronomic management of P is how to induce the transformation of the immobilized P in the solid phase of soils to bioavailable forms. Most P molecules found in soils are insoluble, making them difficult for plants to absorb. The main natural P source in crop soil is the mineral apatite contained in the parental material, and when P is released from rocks by weathering it can cycle mainly by processes of sorption–desorption (interactions between P in soil solution and solid phases), dissolution–precipitation (mineral equilibria), and mineralization–immobilization processes (biologically mediated conversions of P between inorganic and organic forms) (Figure 3) (Weil and Brady, 2017). The adsorption process involves the attraction of phosphate ions to the surface of soil colloids (Bennett and Schipanski, 2013); in this process of "getting fixed" the phosphate ions are converted from a soluble or exchangeable form to a much less soluble or to a nonexchangeable form (Weil and Brady, 2017). The precipitation reactions fix phosphate ions, transforming them into relatively unavailable forms which largely depend upon soil pH. In acid soils, these reactions involve dissolved ions of oxides, or hydrous oxides of Al, Fe or Mn. At moderate pH values, adsorption occurs on the edges of kaolinite or on the Al oxide coating on kaolinite clays. In alkaline and calcareous soils, the reactions involve the precipitation of various calcium phosphate minerals.

Soil P can also be in organic forms, including inositol phosphate and nucleic acids. Organic P accounts for 20 to 80 percent of the total soil P which circulates through mineralization and immobilization processes (Weil and Brady, 2017). Soil P can also be in the soil solution in very low concentrations, generally ranging from 0.001 mg/L in very infertile soils to about 1 mg/L in rich or heavily fertilized soils. Because of the low concentrations of dissolved P in the soil solution the movement via mass flow is limited, therefore the most significant P flows occurs predominantly through diffusion (movement through soil pores in response to a concentration gradient) inside soils (Table 2). All these processes affect the concentration of P in the soil solution and soil solid phases, ultimately regulating the amount of available P for plant uptake, microbial assimilation, and transport to surface and groundwater (Bennett and Schipanski, 2013).

The main P input pathway is fertilization; between 10 and 15 Tg of P are added annually through fertilizers, which represents between 20 and 30 percent of the natural circulation of P in terrestrial ecosystems (Chapin, Matson and Mooney, 2002). Losses of P from soils occur mainly by crop harvest, erosion, and surface runoff, (particulate and dissolved P) and leaching, because gaseous losses of P are negligible.

The P cycle in soils

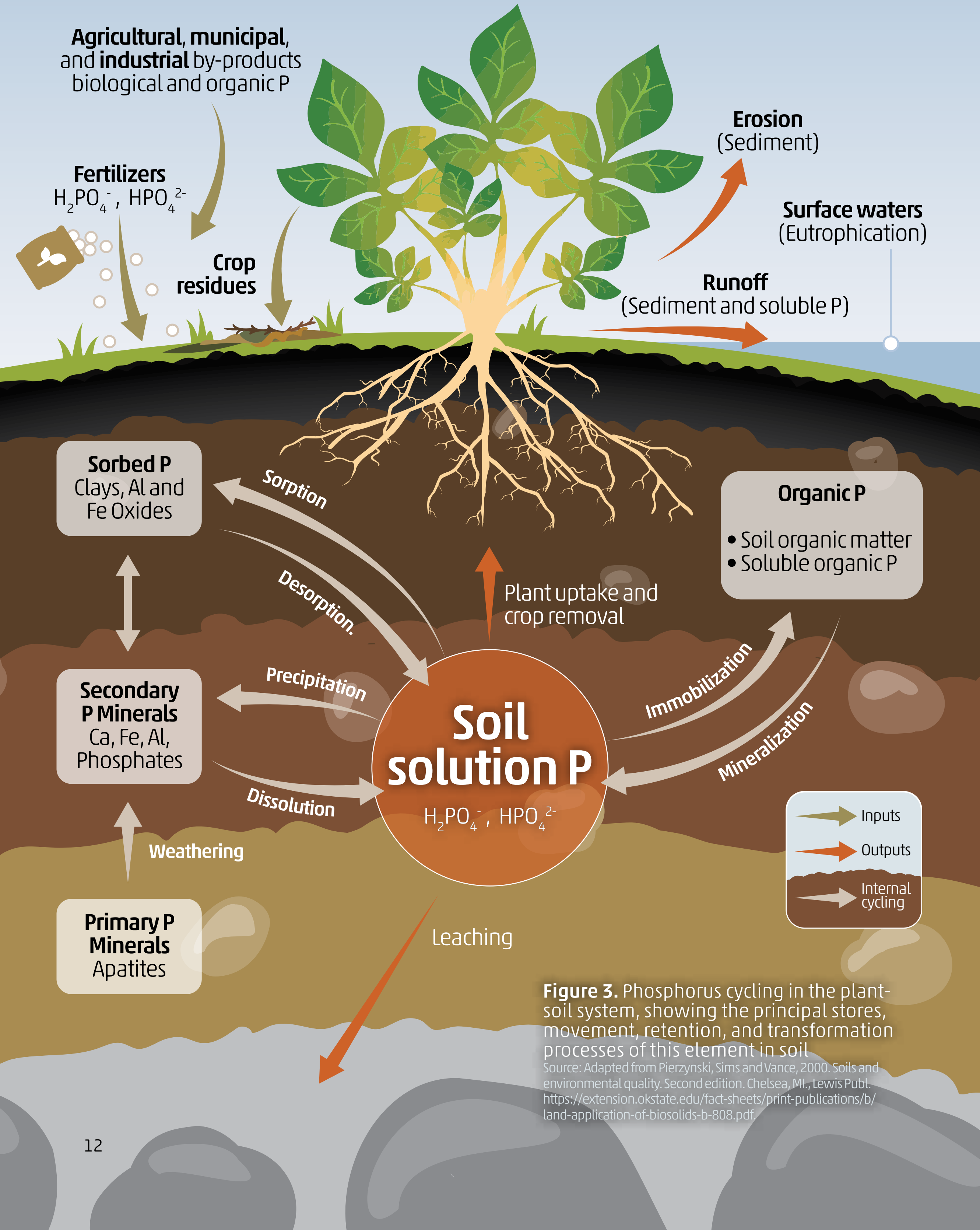
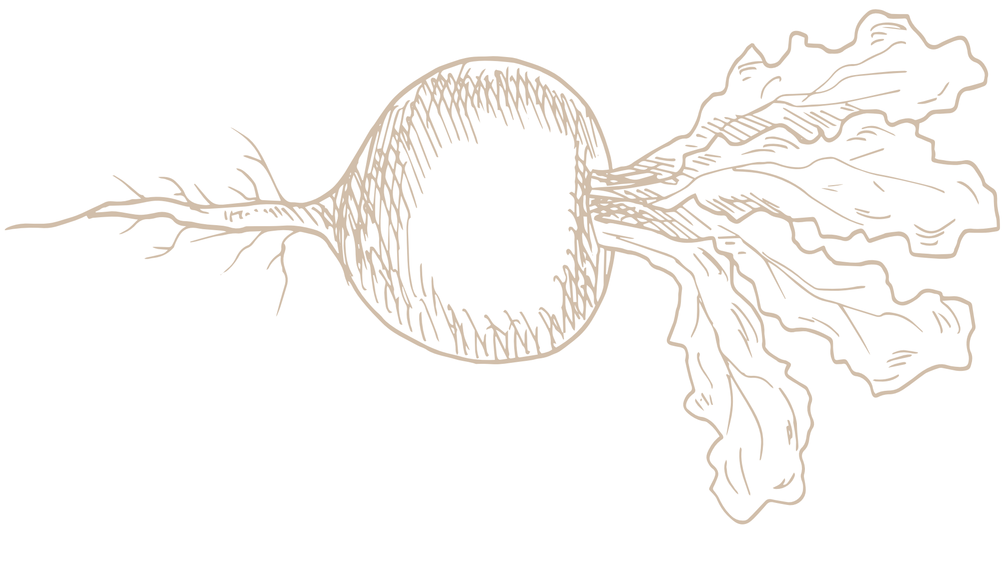


Figure 3. Phosphorus cycling in the plant-soil system, showing the principal stores, movement, retention, and transformation processes of this element in soil

Source: Adapted from Pierzynski, Sims and Vance, 2000. Soils and environmental quality. Second edition. Chelsea, MI., Lewis Publ. https://extension.okstate.edu/fact-sheets/print-publications/b/land-application-of-biosolids-b-808.pdf.

Although K stored in soils accounts for less than two percent of the world's K stocks, soils supply K to many of the world's crops (Brouder, Volenec and Murrell, 2021). In soils, about 98 percent of the K is unavailable for plants and microbes since it is stored in primary minerals. The fraction of plant-available K is generally less than one percent, as shown in Figure 4. Potassium can be found in soils mainly as part of the primary minerals in the form of feldspars or micas. Potassium in the primary minerals account for 90 to 98 percent of the total K content in soils and it is unavailable or only very slowly available for plant uptake. Potassium can also be part of the nonexchangeable pool in secondary minerals (representing about 1 to 10 percent of the total K content in soils) and it is slowly available for plants and microbes. The exchangeable K on soil colloids and the K soluble in water are readily available K pools, however they only represent between 1-2 percent and less than 0.2 % respectively, of the total soil K (Weil and Brady, 2017). Potassium assessments in soils have gained more interest in regions where K balances are negative on a sustained basis leading to K deficiencies in crops and soils. Significant progress has been accomplished in the knowledge of the fundamental mechanisms of K cycling in soils and about its role in plants and animals. Although K is an essential nutrient for crop, animal, and human nutrition, its intake does not meet the minimum requirements in diets of most of the world population. The origin of the deficiency of this element in animals and humans is K-depleted agricultural soils, which, being impoverished in this element, cannot supply plants in adequate quantities, resulting in K-deficient crops that end up contributing to nutritional deficiencies in animals and humans (Bhaskarachary, 2011). Recently, a list of challenges regarding soil K management was developed by Brouder, Volenec and Murrell (2021) and includes: (i) the great variability of K concentration in soils and poor calibration of soil laboratory analysis with crop responses in some areas, which makes the recommendations for fertilization with K less precise; (ii) genetic changes in crops that impact progressive K demand through the growing season and root development that may in turn influence requirements for soil K, and its release to the soil solution; and (iii) abandonment of K soil testing approaches in some parts of the world due to poor access to soil testing or limited supporting correlation, calibration, and interpretation of laboratory soil and plant analysis. In addition, new K-deficient soils have been identified worldwide due to higher harvest rates and the lack of K replenishments in soils.



The global K reserves

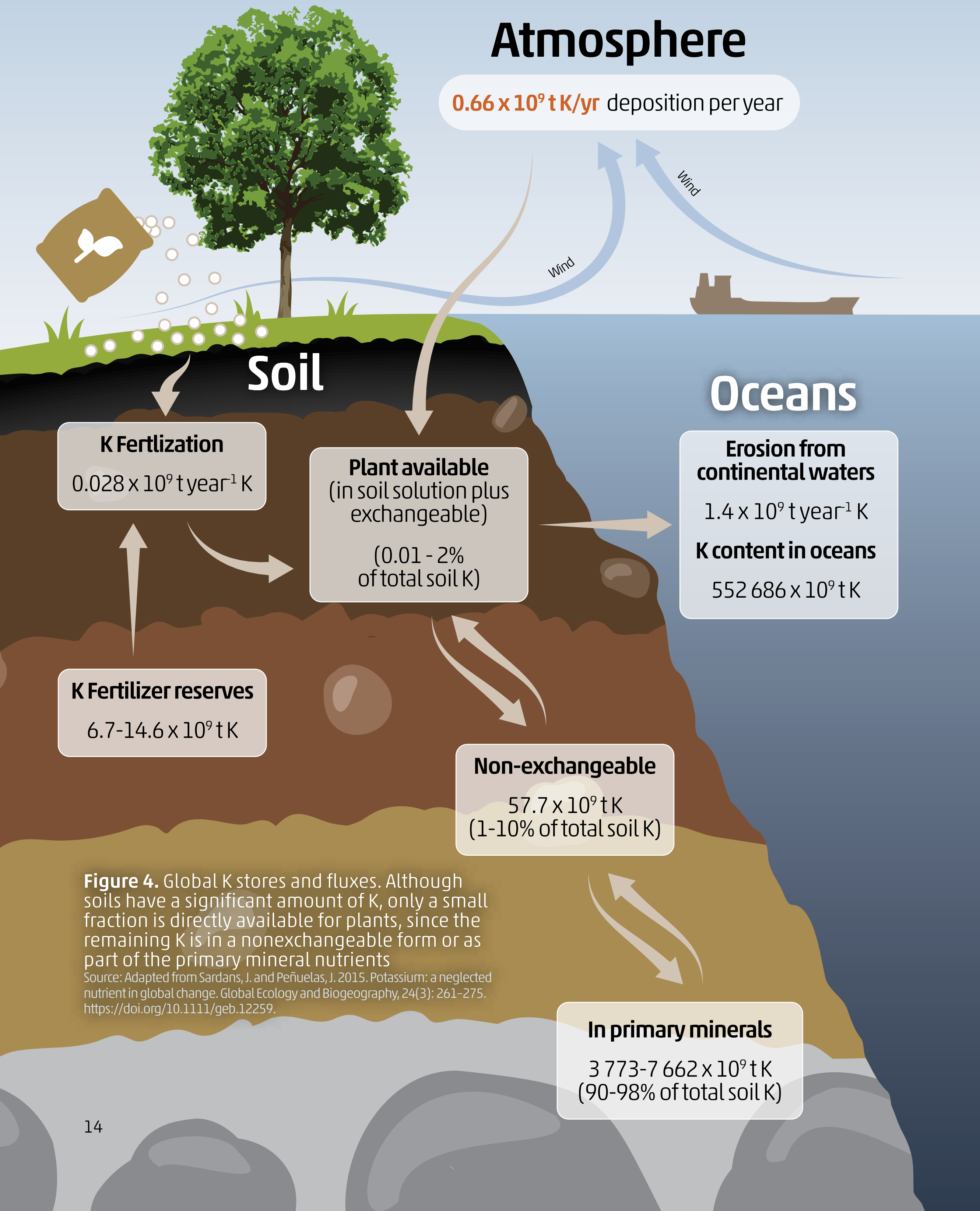


Figure 4. Global K stores and fluxes. Although soils have a significant amount of K, only a small fraction is directly available for plants, since the remaining K is in a nonexchangeable form or as part of the primary mineral nutrients

Source: Adapted from Sardans, J. and Peñuelas, J. 2015. Potassium: a neglected nutrient in global change. Global Ecology and Biogeography, 24(3): 261–275. https://doi.org/10.1111/geb.12259.

Soils are the result of hundreds or thousands of years of pedogenic processes, soil forming factors and weathering of parental material (Bowen, 1979). Weathering transforms the primary geological materials into the compounds from which soils will be formed. It is a process that involves, on the one hand, the destruction of the parent rocks and the minerals that form them by physical, chemical and biological processes. Through these processes new soil particles and secondary minerals are formed, as well as the release of nutrients from these minerals (Weil and Brady, 2017). Therefore, soil nutrient content including macro- and micronutrients (Table 4) is directly influenced by the primary mineral's concentration present in the parental material (Mitchell, 1964). The primarily nutrient concentration found in the different soils is the foundation for the synthesis of secondary minerals (Singh and Schulze, 2015). The secondary minerals modulate the main mechanisms regulating nutrient availability in soils, through adsorption-desorption, dissolution-precipitation, and oxidation-reduction reactions. The interactions among these mechanisms are highly dynamic and can also be greatly influenced by soil microbiologic activity (Horward, 2015).

Table 4. Micronutrient concentration (mg/kg) in rocks
Source: from Stevenson, F.J. and Cole, M.A. 1999. Cycles of soils: carbon, nitrogen, phosphorus, sulfur, Micronutrients. 2nd edition. John Wiley & Sons, Hoboken. 448 pp.

Micronutrient	Granite	Basalt	Lime-stone	Sand-stone	Shale
B	15	5	20	35	100
Cu	10	100	4	30	45
Fe	27000	86000	3800	9800	4700
Mn	400	1500	1100	<100	850
Mo	2	1	0.4	0.2	2.6
Zn	40	100	20	6	95

The soil dry mass (mineral) represents approximately 95-98 percent of its volume while 2-5 percent is composed by organic material. Yet, nine major elements, silicon (Si), O_2, aluminum (Al), iron (Fe), titanium (Ti), Ca, Mg, sodium (Na), and K, make most of the mass of the soil mineral fraction, representing circa of 99 percent. Additionally, 75 other elements, including essential micronutrients, occur at extremely low concentrations, less than 0.1 percent. Some of those elements may cause health issues, as they can be toxic when present at 'high' concentration; these include lead (Pb), cadmium (Cd), and mercury (Hg). These often occur because of pollution caused by human interventions but may also be of natural origin (Davies, 1997).

In addition to soil micronutrient concentration, the chemical form of the micronutrients also plays a role on soil micronutrient availability, deficiencies, and toxicities. Micronutrients can be present in soil as inorganic forms (silicates, oxides, sulfides), and organic forms (micronutrient chelation by organic substances of SOM). Table 5 lists the common range of micronutrient concentrations commonly found in mineral soils in different regions of the world and their dominant form in the soil solution.

Table 5. Concentration range of some micronutrients[1] in mineral soil and its commonly found forms of in the soil solution.

Source: from Sillanpää, M. 1982. Micronutrients and the nutrient status of soils: A global study. FAO Soils Bulletin 0253. Rome, Italy, FAO. 458 pp. https://www.fao.org/publications/card/en/c/03daab96-5a01-4ef1-96a1-76ba6b1c9343/

Adapted from Davies, B.E. 1997. Deficiencies and toxicities of trace elements and micronutrients in tropical soils: Limitations of knowledge and future research needs. Environmental Toxicology and Chemistry, 16(1): 75–83. https://doi.org/10.1002/etc.5620160108.

Micronutrient	Regions			Dominant soil solution forms
	Global[2]	Temperate[3]	Tropical[4]	
Manganese	34.8	28.3	44.3	Mn^{2+}
Zinc	2.4	2.6	1.8	Zn^{2+}, $Zn(OH)^{+}$
Copper	5.6	5.7	5.8	Cu^{2+}, $Cu(OH)^{+}$
Molybdenum	0.2	0.3	0.2	MoO_4^{2-}, $HMoO_4^{-}$
Boron	0.6	0.7	0.5	H_3BO_3, $H_2BO_3^{-}$

[1] Micronutrient as mg/L
[2] Average of 1635 samples from 21 countries
[3] Average of 1244 samples from 5 countries
[4] Average of 391 samples from 16 countries

Although soils may have a substantial amount of nutrients, their availability can be limited due to several reasons, such as natural deficiencies, nutrients that are in highly immobilized forms in the solid phase, or due to degradation processes related to improper soil management. The WRSR (FAO, 2015) documents the extent to which soil fertility has been affected by unsustainable management practices. These practices, based on extractive and intensive farming systems (Lal, 2009), negatively affect soil productivity and lead to serious nutrient deficiencies in the harvested crops. Because of soil degradation worldwide, soil in many regions is becoming less fertile, and is losing its capacity to provide nutrients to plants, animals and people who rely upon them.

1.2. Soil fertility loss and crop production

Soil fertility varies due to factors related to the parent material, climate, vegetation and land use (Augusto *et al.*, 2017). There are areas of the world with naturally high or low soil fertility. An example of naturally fertile soils are black soils found in mid-latitudes of North America, Eurasia, and South America (Figure 5)(Kravchenko *et al.*, 2011; Liu *et al.*, 2012; Rubio, Pereyra and Taboada, 2019). In contrast, other regions have naturally low soil fertility, low SOM content and high acidity (Barrett and Bevis, 2015; FAO, 2015). Harsh climates (e.g. very cold, or very arid) also play a role in lowering soil nutrient levels (Alewell *et al.*, 2020). Most ecosystems of the world are limited by N and/or P. In the case of N limitation this is best explained by climate effects that are less important in temperate zones and in soils with moderate to high organic matter contents. In contrast, P crop limitation is less regulated by climatic conditions, and more influenced by the mineralogical characteristics, soil type and parent materials (Augusto *et al.*, 2017).

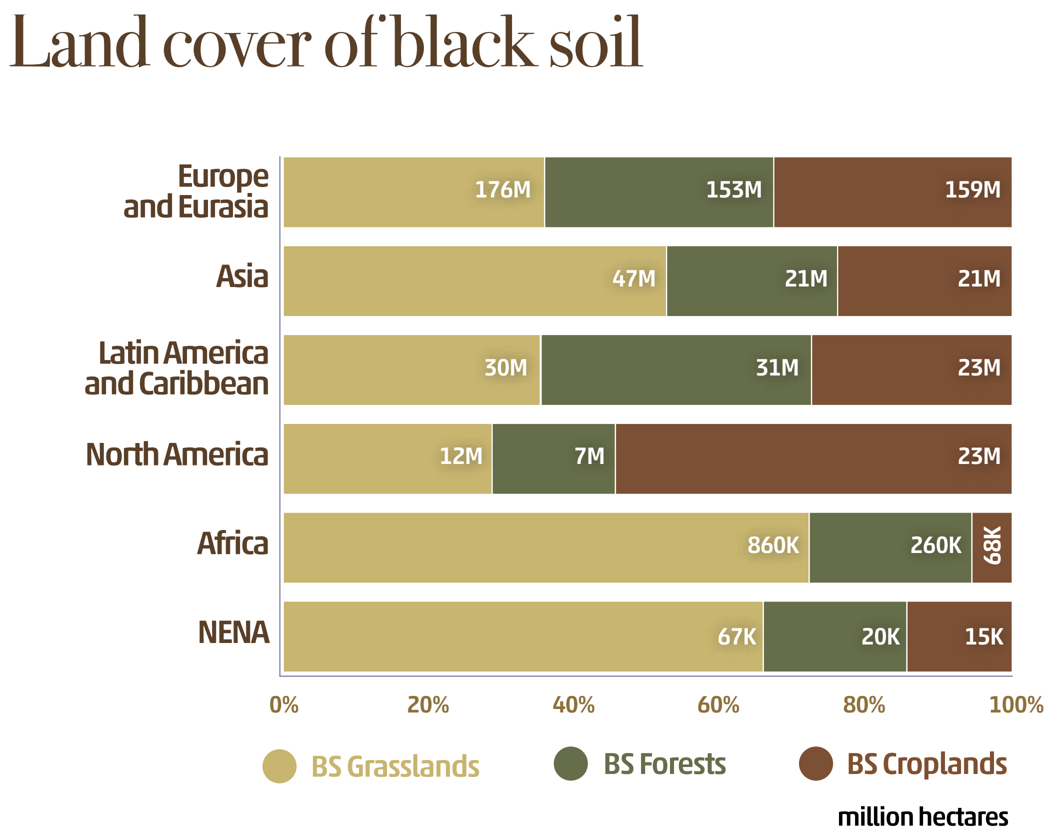


Figure 5. The global terrestrial surface covered by black soils distributed in the different regions of the world

Source: Adapted from FAO. 2022. Global Map of Black Soils. Rome, Italy, FAO. https://www.fao.org/documents/card/es/c/cc0236en/

Although low fertility is a natural feature of some soils, in others fertility is reduced or lost due to degradation processes, which affect up to 33 percent of global soils (FAO, 2015). These processes include erosion, reduction of organic carbon in the soil and effects on biodiversity, acidification, salinization, urbanization, sealing and nutrient imbalance mainly caused by unsustainable soil management practices (FAO, 2015). Agricultural systems lose nutrients with each harvest, and if soils are not managed sustainably, fertility is progressively lost. Global harvested crop N was 73 Tg N/yr in 2010, while the total inputs were 161, leading to a N surplus of 86 in 2010 (Zhang *et al.*, 2020). Nitrogen surplus is evidence that the use efficiency of this nutrient is low. N use efficiency has been estimated to have decreased from 53 percent in the 1960s to 44 percent in the 2010s (Zhang *et al.*, 2021). This means that nearly half of the N applied is unused by plants in the year it is applied. In the case of P, the application of fertilizer to agricultural soils increased by 3 percent annually (from 2002 to 2010), and soil P deficit still prevail in 32 percent of the world's cropland and 43 percent of the pasture (Lun *et al.*, 2018). With regard to regional P balances, some regions in America and Europe have negative P balances (e.g. net P losses from agricultural systems, while others including Asia, Oceania and Australia have net P accumulation.
Despite these regional N and P surpluses, deficits are still observed, which indicates that fertilizers use optimization is urgently required. To overcome naturally low soil nutrient content and depleted nutrient content due to unsustainable practices, fertilizers have been applied, but inequalities in fertilizer applications are commonly observed. For example, across most of sub-Saharan Africa (SSA) access to mineral N fertilizers is limited, and fertilizer application rates are about 8–10 kg N/ha/year as compared with ten times this amount in many developed countries (Vitousek *et al.*, 2009). It has been estimated annual total nutrient deficits of 5.5 Tg N, 2.3 Tg P, and 12.2 Tg K, and potential worldwide production losses of more than one teragram of these nutrients per year (Tan, Lal, and Wiebe, 2005).

Unsustainable agricultural practices, lack of resources and capacity development and nutrient underuse in sub-Saharan Africa (SSA) have resulted in significant soil nutrient depletion, low crop yields, and poverty, leaving many farm families in a scenario of vulnerability and food insecurity. The situation is aggravated by low use of fertilizers by farmers (Chianu, Chianu and Mairura, *2011*) and increasing soil degradation that is affecting SOM, pH, and cation exchange capacity (Tully *et al.*, 2015). Decades of nutrient mining have depleted soil fertility, putting the region's food security at risk (Bekunda, Sanginga and Woomer, 2010). There are some regions in South America with high rates of chemical fertilizer applications, and high losses as well, mainly through erosion and high P exports derived from organic P management. In contrast, the eastern European Union has shown low erosion losses and low chemical fertilizer input (Alewell *et al.*, 2020).

The supply of P is essential not only for croplands but also for other productive systems such as grasslands. Natural and induced grasslands support livestock grazing and receive no mineral fertilizer. To accomplish the 80 percent increase in grass production (for the dairy and meat industries) while preserving soil P levels, mineral and organic fertilization in grasslands would have to grow more than fourfold in 2050 compared to 2005 (Sattari *et al.*, 2016).

Fertility loss is not exclusively due to the loss of macronutrients. Soil micronutrients deficiencies are widespread around the globe, with 49 percent of soils deficient in Zn, 31 percent deficient in B, 15 percent deficient in Mo, 10 percent deficient in Mn and 3 percent deficient in Fe (Sillanpää, 1982, 1990; Bowell and Ansah, 1993; Graham, 2008). For example, 40 percent of African soils have naturally low soil fertility but degradation processes such as nutrient mining have reduced it even further. In some areas of SSA, micronutrient deficiencies can be particularly pronounced (Nube and Voortman, 2011) as the soil has undergone nutrient mining over an extended period. In India, soil Zn deficiency is present in 47 percent of the soils (Rathore *et al.*, 1980; Katyal and Vlek, 1985), and in Indonesia (Southeast Asian region) 29 percent of soils (Welch *et al.*, 1991). The consumption of food with low nutritional value is also underlined by soil mismanagement and degradation issues. Therefore, the transformation of food production systems which includes the adoption of SSM is critical to support the provision of high-density nutrition food. 'Nutrient-sensitive agriculture' which is a complex approach with different pathways has been reckoned as an efficient alternative to overcome this issue of micronutrient deficiencies and associated health problems.

1.3. Assessing, mapping, and monitoring soil fertility: towards a global soil nutrient budget.

The accelerated use of nutrients for crop production and other human activities has significantly impacted and modified the global nutrient cycles in the planet, especially for N and P (Sutton *et al.*, 2013; Steffen *et al.,* 2015). Despite the critical role played by nutrients such as N, P, and other macro and micronutrients, their significance in global challenges such as climate change and contamination has gotten far less public attention than other drivers of environmental change including CO_2 and non-CO_2 emissions (Sutton *et al.*, 2013).

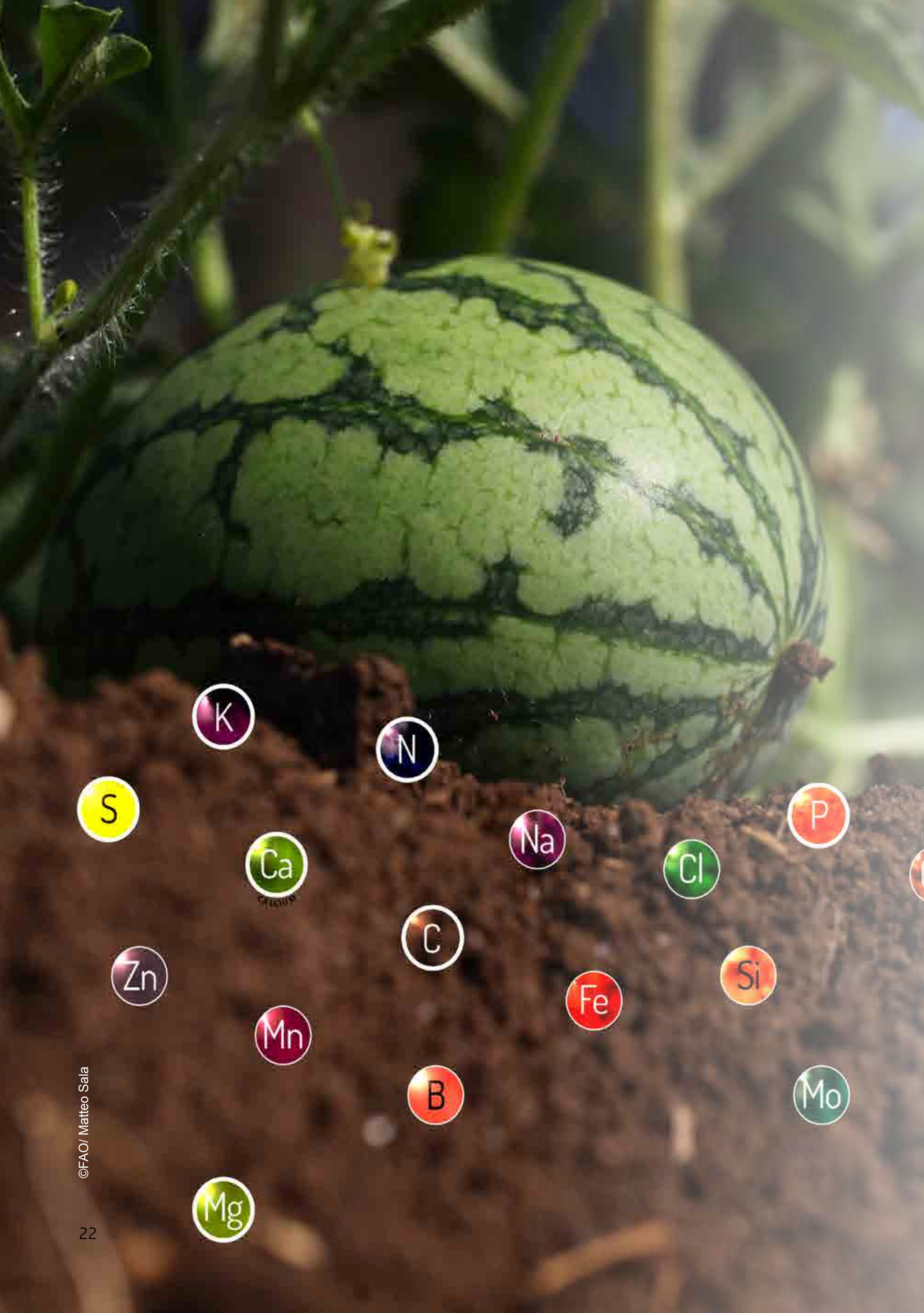
Since soil fertility is not static and it is linked to degradation processes and soil fertility loss, soil mapping and fertility modelling efforts should be based on a soil monitoring system capable of accurately representing the actual soil conditions through time and at an appropriate scale. Evidence-based decision making on soil fertility requires data and information about the status, availability, and dynamics of soil nutrients at plot level if planning a fertilization action, or at national, regional, and global levels for balances, policy advice and resource management. Monitoring data and information are also key for the development of policies and actions regarding soil fertility and fertilizers use. Understanding the status and spatial trends of soil nutrients is key to guide policymaking in a coordinated and data-driven way to close yield gaps and reduce the pressure on natural resources upon which many communities rely.

Overtime, there have been different efforts to quantify soil nutrient budgets. Hence it is important to understand the state of the art and identify the gaps that need to be addressed with solid information and trends about availability (both natural and human added) of soil nutrients in the soils to guide better interventions. More recently, Hengl *et al.* (2017) used a digital soil mapping approach to predict 15 soil nutrients at a 250 m resolution in Africa, using a random forest model (Wright and Ziegler, 2016). In the case of K, information on the spatial distribution of global reserves has been less documented, even though this element is limiting in 70 percent of terrestrial ecosystems (Sardans and Pañuelas, 2015). An important factor that must be considered when dealing with the spatial distribution of K is depth. Recent studies indicate that the vertical stratification of K is not pronounced, so that not considering storage of this element at depths greater than 20 cm could lead to the underestimation of K storage in soils (Correndo *et al.*, 2021).

Soil fertility data and information are key resources for making proper fertilization recommendations. These decisions and recommendations are based on the 4R approach (4R Nutrient Stewardship), which seeks to apply nutrients with the right rate, the right location, at the right time and from the right source. The fertilizer industry established the 4R approach as a process to guide fertilizer best management practices in many parts of the world (Johnston and Bruulsema, 2014). Slaton *et al.* (2022) have established a core set of required and recommended information from United States soil test P and K correlation and calibration investigations. Slaton and collaborators (2022) developed a Fertilizer Recommendation Support Tool, consisting of a national database that will support a soil-test-based nutrient management decision aid tool, and similar examples have been developed around the world. This type of information supports modeling, and the development of various decision-support systems can increase agricultural efficiency while reducing environmental problems caused by excess nutrient losses.

Tziolas *et al.* (2021) reviewed the most efficient practices for the advancement of an Earth-Observation data-driven soil mapping. The most frequent limitations that hinder its implementation are the area covered and data to be shared, thresholds for bare soil and soil surface detection, and infrastructure and capacities. According to Tziolas *et al.* (2021) the best practices for advancement on Earth-Observation data-driven soil mapping include: (i) the major boost of recent artificial intelligence techniques to increase representativeness and reliability; (ii) harmonization of labelled datasets; (iii) data fusion with *in situ* sensing systems; (iv) a continued effort to overcome the current limitations in terms of sensor resolution and processing of this Earth-Observation data; and (v) political and administrative issues (e.g. funding, sustainability). Drawbacks of this type of approach include the low availability to most stakeholders involved in soil nutrient management, and the fact that the applicability of this methodology in mapping soil nutrient content is uncertain.

Internet of Things (IoT) is "an open and comprehensive network of intelligent objects that have the capacity to auto-organize, share information, data and resources, reacting and acting in face of situations and changes in the environment" (Ashton, 2009). Crop management can benefit from the IoT in terms of accessibility, cost savings, and efficiency, thanks to the timeliness of interventions. It is becoming widely used as an approach to crop management issues, including soil fertility and fertilizer use, most of which are yet unsolved (Vitali *et al.*, 2021). The IoT approach has been used for addressing relevant factors in agriculture including weather, water availability, pests and diseases and GHG emissions. Examples of applications in the soil fertility field is the use of soil water sensors for inferring information about soil nutrient content, and the observation of nutritional crop status from multispectral and hyperspectral camera sensors set on field cameras (Vitali *et al.*, 2021). However, caution should be exercised in expecting the use of tools such as IoT. As Vitali *et al.* (2021) argue "Excitement in Internet of Things is pumping the belief that many less expensive sensors could increase data granularity in space and time with an acceptable decrease in data quality. However, data (sensor) reliability remains a fundamental aspect of any technology".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2. The role of soil fertility on crop, animal, and human nutrition

2.1. Soil fertility and human health

Whether the impacts are positive or negative, direct or indirect, soil has a significant impact on human health. There is abundant historical evidence from the time of the Greek and Roman civilizations linking soils to human health. Keesstra *et al.* (2016) highlighted the important links of soil science to several of the SDGs, showing how soil functions are linked to the ecosystem services and human well being. A number of articles quoted by Brevik and Sauer (2015) have been published over the last 10 years reviewing the status of our knowledge of soils and human health. Contemporary research has revealed that soils have an impact on human health through influencing food availability and quality (food security), as well as human exposure to numerous pollutants and pathogens (Brevik, 2013; Burras, Nyasimi and Butler, 2013).

The research about soils and human health addresses a wide range of subjects. The transmission of nutrients from soil to people is one of the primary topics. This could be a transfer from soils to plants to people, a transfer from soils to plants to animals to people, or a direct transfer from soils to people.

Soils are the primary source of essential nutrients that nourish humans and other animals (Mitchell and Burridge, 1979).

According to Steffen *et al.* (2018), approaches like soil security may provide a framework within which interdisciplinary and transdisciplinary approaches can be used to explore issues related to soil and human health. McBratney, Field and Koch (2014) identified five dimensions of soil security, and each of them are linked to human health (Brevik *et al.*, 2017) (Table 6).

Table 6. Some cases of links between dimensions of soil security and human health

Source: Adapted from Brevik, E.C., Steffan, J.J., Burgess, L.C. and Cerdà, A. 2017. Links between soil security and the influence of soil on human health. In D.J. Field, C.L.S. Morgan and A.B. McBratney, eds. Global Soil Security, pp. 261–274. Progress in Soil Science. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-43394-3_24.

Dimension of soil security	Links to human health
1. Capability	Production of plenty food
	Ability to pass essential nutrients up the food web
	Waste filtration function of soils, particularly in the supply of clean water
2. Condition	Ability to pass essential nutrients up the food web
	Presence or absence of potentially harmful chemicals or organisms
3. Capital	Ecosystem services that support human health have value
	Soil conditions that negatively influence human health have a cost
	Medicines developed from soils or soil organisms have economic value and save money when they shorten or prevent illnes
4. Connectivity	The value that society places on soils influences how soils are managed or treated, which in turn influences soil condition
	The terroir concept provides an example of a way to connect people to the soils that produce their food and encourage a more positive image of soil and better management
	Contact with healthy soil has been shown to have potential human health benefits
5. Codification	Government-sponsored conservation programmes can improve soil and water quality, leading to human health benefits
	Non-binding initiatives such as the United Nations proposed Sustainable Development Goals can positively influence soil and water quality and thus human health through capability and condition

One of the main connections of soils with human health is malnutrition. Human micronutrient deficiency is defined as a lack of essential vitamins and minerals in the diet. Micronutrients enable the body to produce enzymes, hormones and other substances that are essential for proper growth and development (WHO, 2022). Micronutrient deficiency is a major threat to the health and development of the population particularly affecting children and pregnant women in low-income countries (WHO, 2022). Besides undernourishment, micronutrient deficiency also underlines other health issues including overweight, obesity, cardiovascular diseases, certain cancers and diabetes (WHO, 2022). Human micronutrient demands are very small in quantity when compared to macronutrient demands. To meet the main human micronutrient needs, the proper supply of Fe, Zn, Ca, iodine (I), vitamin A, complex B vitamins, and vitamin C is necessary, although other micronutrients also play important roles on human and plant health - e.g. selenium (Se).

The health issues related to each micronutrient deficiency vary (Table 7), and they can be co-dependent. To list a few: Fe deficiency is the underline cause of anemia, particularly affecting pregnant women, young women (from 15 to 19 years old) and infants (WHO, 2015); Zn deficiency can impair the functionality of the central nervous, gastrointestinal, immune, epidermal, reproductive and skeletal systems (Jurowski *et al.*, 2014). Iron deficiency in 2000 was estimated at 50 percent of the global population and similar estimates have been made for Zn deficiency (Cakmak, 2002; Welch and Graham, 2005; Alloy, 2008). In fact, micronutrient deficiencies are now recognized as one of the leading causes of worldwide illness burden (Kenz and Graham, 2013).

Table 7. Micronutrient deficiencies in humans and effects on human health.
Source: Adapted from Wakeel, A., Farooq, M., Bashir, K. and Ozturk, L. 2018. Micronutrient malnutrition and biofortification: recent advances and future perspectives. Plant Micronutrient Use Efficiency, pp. 225-243. https://doi.org/10.1016/B978-0-12-812104-7.00017-4.

Micronutrient	Effects
Iron (Fe)	Anemia, impaired motor and cognitive development, increased risk of maternal mortality, premature births, low birthweight, low energy
Zinc (Zn)	Weakened immune system, increased exposure to infections, stunning
Iodine (I)	Brain damage in newborns, reduced mental capacity
Vitamin A	Severe visual impairment, blindness, increase risk of severe illness and death from common infections, as diarrhea and measles in preschool age children; night blindness in pregnant women, increased risk of death

Globally, the cause of malnutrition is not only due to insufficient calorie intake, but it is also the result of a poor micronutrient intake/diet, as human diet is essentially dependent on the cultivation of only 12 crops which accounts for 75 percent of the global crop production (Scientific Panel on Responsible Plant Nutrition, 2020). In 2014 the United States Department of Agriculture reported a decline in the food nutritional value (Table 8) mainly due to the change in varieties whereas breeding programs have historically, focused only on yield gain and lead to a tradeoff between yield and nutrient content (Davis, Epp and Riordan, 2004).

Table 8. Average nutritional value decline in 43 crops between 1950-1999.
Source: Adapted from Davis, D.R., Epp, M.D. and Riordan, H.D. 2004. Changes in USDA food composition data for 43 garden crops, 1950 to 1999. Journal of the American College of Nutrition, 23(6): 669–682. https://doi.org/10.1080/07315724.2004.10719409.

Nutrient	Percentage
Vitamin C	15
Vitamin B12	38
Protein	6
Iron	15
Calcium	16
Phosphorus	9

A healthy and diversified diet that includes fruits, vegetables, legumes and animal sources consumption (Table 9) are out of reach for 3 billion people (FAO, IFAD, UNICEF, WFP and WHO, 2021). All these factors together increase the risk for widespread micronutrient deficiency, increasing morbidity and mortality. The whole food chain production system, focused solely on spiking-up crop yield commodities, has severely compromised crop nutritional value (Miller and Welch, 2013). However, sustaining a healthy diet can cost up to 60 percent more than a diet that just includes basic nutrients, and approximately five times more than a diet that meets the bare minimum of energy requirements through the consumption of starch-rich foods (FAO, IFAD, UNICEF, WFP and WHO, 2021).

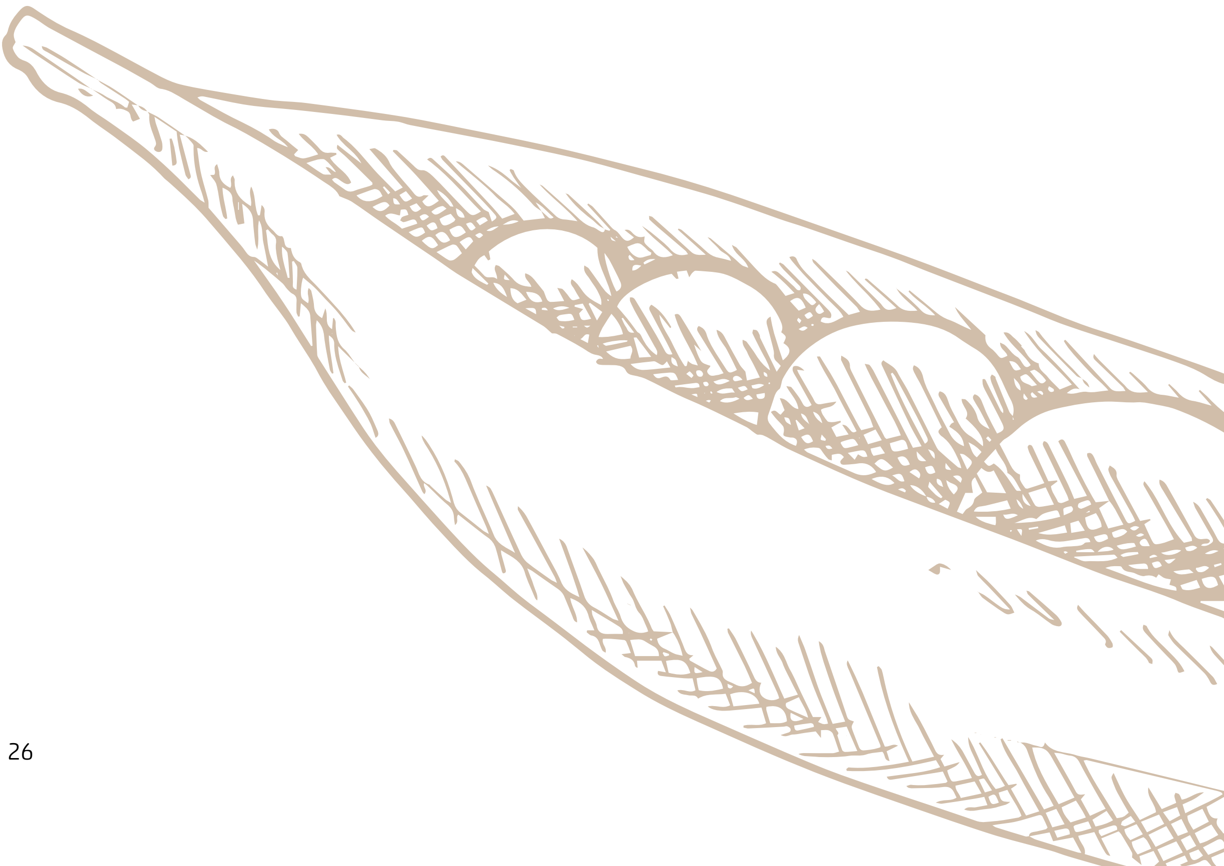

Table 9. Food groups nutritional values, in percentage of the total required for a balanced-healthy diet.

Source: Adapted from Bai, Y., Alemu, R., Block, S.A., Headey, D. and Masters, W.A. 2021. Cost and affordability of nutritious diets at retail prices: Evidence from 177 countries. Food Policy, 99: 101983. https://doi.org/10.1016/j.foodpol.2020.101983.

Nutritional indicator	Starchy Staples	Vegetables and legumes	Fruits and nuts	Meat	Dairy and eggs	Oils and fats	Fish and seafood
Energy	65.6	8.4	4.6	0.4	4.4	15.0	0.7
Element							
Iron	60.1	31.8	4.1	2.1	0.4	0.1	1.2
Zinc	67.2	18.9	5.4	2.5	4.8		1.1
Copper	47.8	22.3	7.7	20.7	0.5		0.8
Selenium	87.6	3.0	1.1	2.2	2.8		3.2
Vitamins							
Vitamin C	14.9	59.7	20.4	0.3	1.1		0.1
Vitamin A	3.3	48.1	0.5	39.3	8.1	0.2	0.5
Vitamin B6	70.3	19.4	3.8	3.2	2.4		0.7
Vit. B12	0.2			73.6	9.7		16.5

According to UNICEF, WHO and World Bank (2021), approximately half of child mortality under 5 years old is related to malnutrition. Food insecurity and malnutrition impacts human health in different ways (Table 10), e.g. hunger and undernutrition, obesity and overnutrition and micronutrient deficiency related diseases.

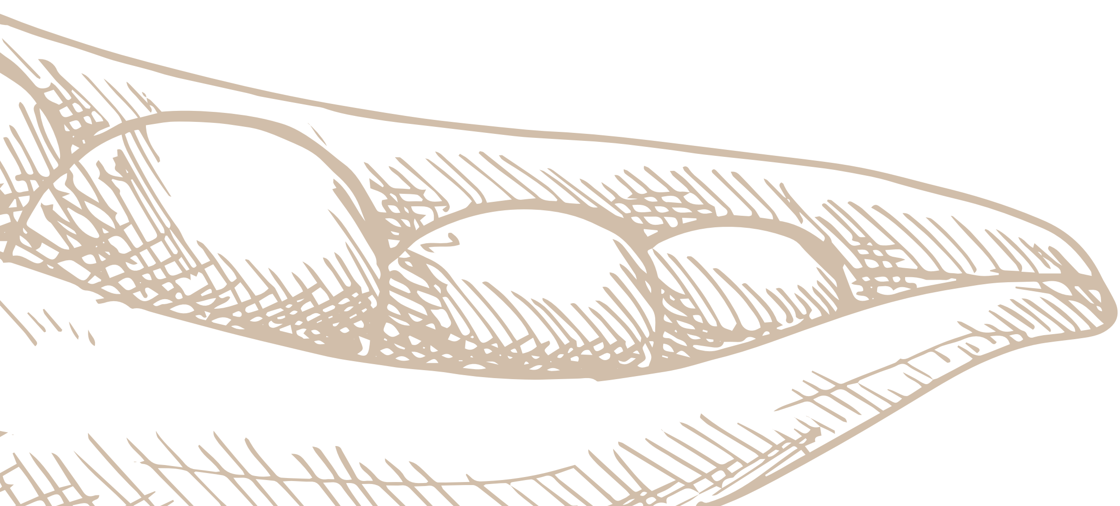

Table 10. The status of undernourishment and food insecurity in the world, 2018-2020
Source: Adapted from FAO, IFAD, UNICEF, WFP and WHO. 2021. The State of Food Security and Nutrition in the World 2021: Transforming food systems for food security, improved nutrition and affordable healthy diets for all. The State of Food Security and Nutrition in the World (SOFI) 2021. Rome, Italy, FAO. 240 pp. https://doi.org/10.4060/cb4474en
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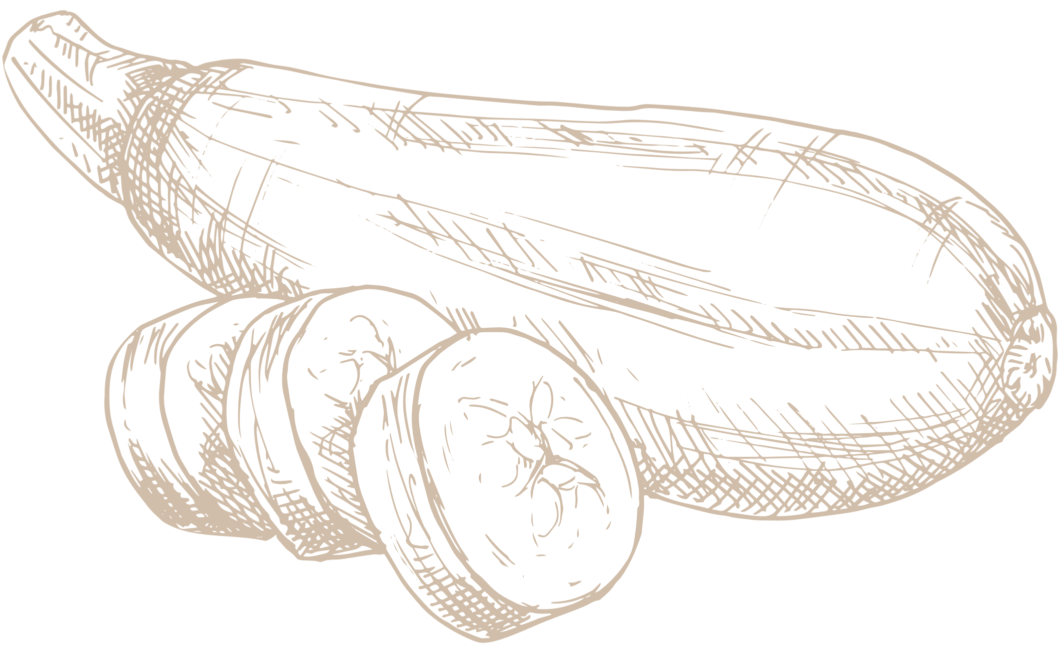
Regions	Undernourishment	Food Insecurity Moderate or severe
	percentage	
World	8.9	27.6
Africa	18.9	55.5
Asia	8.2	23.6
Latin America and the Caribbean	7.7	34.8
Oceania	6.2	12.9
Northern America and Europe	<2.5	8.0

2.2. Soil fertility and crop nutrition

Nutrient-deficient soils will produce nutrient-deficient plants, ultimately causing people suffering with nutrient deficiencies. The chronic lack of micronutrients derived from nutrient-deficient soils and crops cause severe and invisible health problems known as hidden hunger, which affects more than 2 billion people in the world (WHO, 2016). Globally, about two-thirds of the world's population is at risk of deficiency in one or more essential mineral elements (White and Broadley, 2009). Malnutrition or hidden hunger is caused due to, in part, unsustainable agricultural practices that have focused only on maximizing crop yields and, therefore, have led to a decline in food nutritional value (Mayer *et al.*, 2020). Several studies have shown the close relationship between nutrient deficiency in soils and nutrient deficiency in humans in Africa. In 2017, Cakmak, McLaughlin and White highlighted the geographical overlap between areas with soil Zn deficiency and areas showing human Zn deficiencies. In this publication, the authors indicate the narrow relationship among these deficiencies. Other studies show the variation in human Se nutrition is highly variable and part of this variation is linked to the influence of soil types on Se content in crops. Therefore, Se deficiencies are spatially dependent (Belay *et al.*, 2020). The factors that have the greatest influence on crop micronutrient concentration and covary with grain micronutrient concentration are soil organic matter content, temperature, pH and topography. These results show the close relationship between the physicochemical and biological characteristics of soils and the concentration of micronutrients in crops (Gashu *et al.*, 2021). Complex scenarios also occur in other regions of the world such as the Middle East–West Asia where several combined factors contribute to food insecurity, including low agricultural yields associated with drought, abundance of calcareous soils, low SOM content, limited access and scarcity of fertilizers and nutrient deficiencies in soils. These conditions make Zn and Fe deficiencies in soils particularly pronounced (Ryan *et al.*, 2013).

Soil micronutrient cycling relies on several edaphic and biological factors, such as soil pH, redox potential, co-interactions with other ions, soil mineralogy and organic matter content, microbial activity and diversity (Dhaliwal *et al.*, 2019). In fact, soil physical, chemical and biological properties underpin the complexity of the processes and interactions regulating macro and micronutrients availability and, or deficiency in the soil (Jones and Darrah, 1994). Soil nutrient content including macro and micronutrients is directly influenced by the primary mineral concentration present in the parent material (Table 4). Table 4 lists the range of micronutrient concentration that are commonly found in mineral soils in different regions of the world and their dominant form in the soil solution. In general, the higher is the soil clay content (soil secondary minerals), the stronger is the retention of positively charged micronutrients (e.g. Zn^{+2}, Fe^{+2}, Cu^{+2}, Mn^{+2}) by soil colloids, countering leaching (Kenz and Graham, 2013) and nutrient losses. The availability of cationic micronutrients commonly decreases with increase of pH, as opposed to the ionic micronutrient (e.g. Mo^{-}, Cl^{-}). For example, in Malawi over 80 percent of rural households living on low-pH soils (acidic soils) had inadequate dietary Se supplies compared to 55 percent on calcareous soils. In addition, in areas with non-calcareous soil and low pH, an inadequate supply of Ca, Se, and Zn were observed in more than 80 percent of the poorest rural households (Joy *et al.*, 2015, 2015a).

Soil organic matter (SOM) has a leading role regulating the physicochemical reactions that drive the micronutrients availability in agricultural soils (Dhaliwal *et al.*, 2019). The organic compounds - part of the SOM - from the microbial activity and roots exudates can bind to some micronutrients through chelation reactions resulting in the formation of more stable complexes of micronutrients (Neumann and Römheld, 2012). The SOM can contribute with 20-70 percent of the soil cation exchange capacity (CEC) and increase micronutrient availability (Fe, Mn, Zn, Cu, Co) (Stevenson, 1994) (Figure 6). Equally, soil microorganisms can produce organic acids (citric, tartic, malic and α-ketogluconic) that can form chemical complexes with metallic cations in the soil and minimize potential toxicity (Stevenson and Cole, 1999).



The soil cation exchange capacity

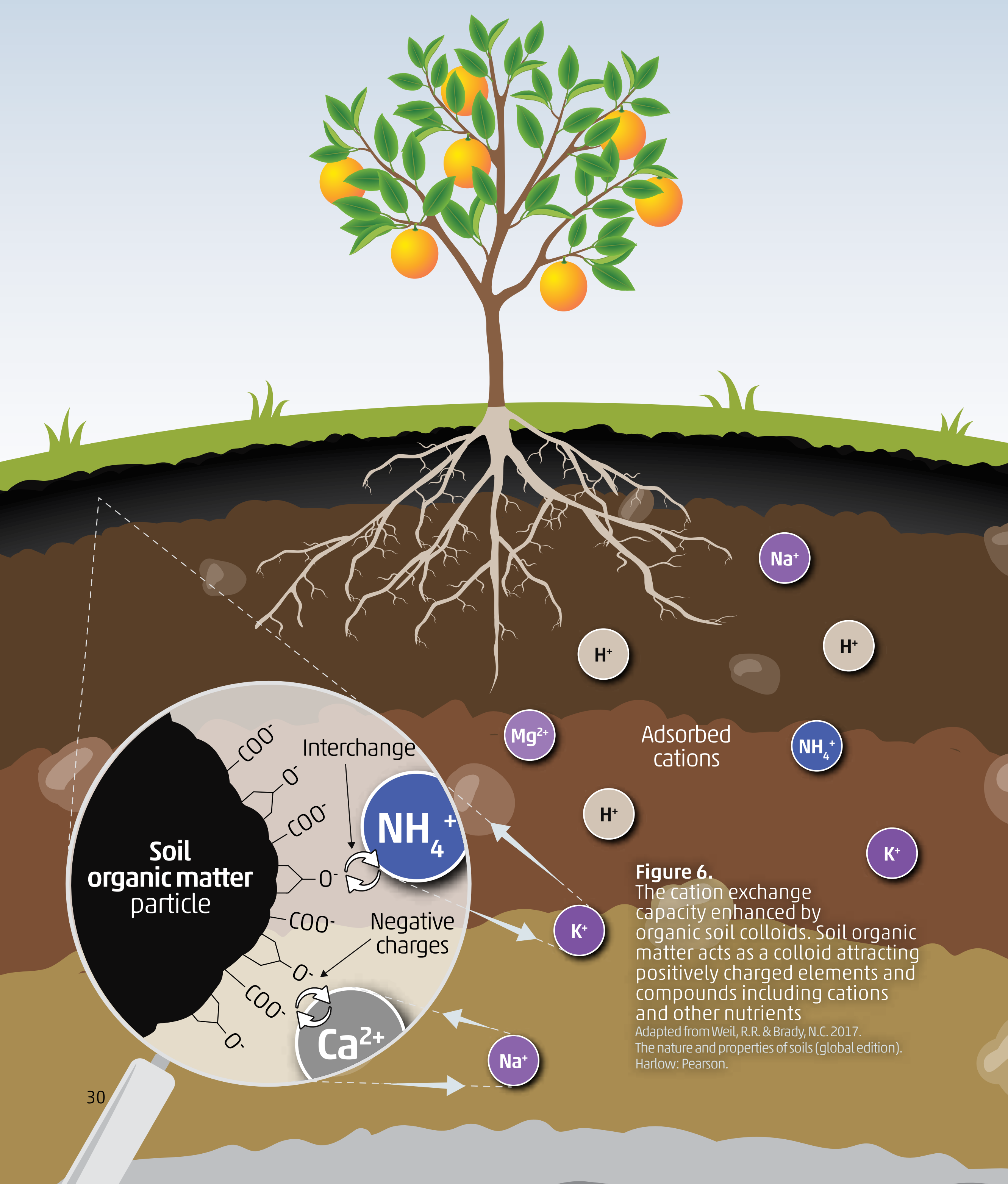


Figure 6.
The cation exchange capacity enhanced by organic soil colloids. Soil organic matter acts as a colloid attracting positively charged elements and compounds including cations and other nutrients
Adapted from Weil, R.R. & Brady, N.C. 2017. The nature and properties of soils (global edition). Harlow: Pearson.

2.3. Strategies to increase soil macronutrient and micronutrient availability and the role of fertilizers in crop production and nutrition

The understanding of the processes that regulate nutrient availability, soil properties, and environmental conditions, need to be improved to be further harnessed and adapted to a wider geographic extend. Only then, it can effectively enable the implementation of bespoke fertilization-practices that can improve micronutrient management and support soil and human health. To address the issues related to organic and chemical nutrient management, not only the technical and scientific data-driven knowledge needs improvement, but also issues related to the lack of resources must be addressed.

A balanced application of micronutrients to soils, through organic amendments alone or in combination with chemical fertilizers, is a feasible option to enhance micronutrient availability (Mortvedt, 1985; Malavolta, 1996; Heisey and Mwangi, 1996; Rengel, Batten and Crowley, 1999; Graham, 2008; Kihara *et al.*, 2020; IPCC, 2021). For example, the application of Zn-enriched urea (three percent) has increased rice nutritional value by 56 percent and yield by 23 percent in India (Shivay, Kumar and Prasad, 2008). A similar effect on the Zn enrichment content in cereal grains has been observed in Turkey (Cakmak, 2009).
A review from Africa reported a positive impact of Zn fertilization on maize productivity and pointed out that both organic and inorganic Zn application supported not only grain yield increases but the benefits were even greater on grain nutritional quality, in 60-80 percent of the cases (Kihara *et al.*, 2017). An additional benefit was the suppression of root pathogens and root nematode infestation (Graham and Webb, 1991).

Yield increases due to micronutrient fertilization - mainly focused on Zn fertilization - have been observed worldwide, although the amplitude of those yield gains is highly variable (e.g. Zn fertilization can reach an average yield gain of 30 percent) (Mortvedt, 1995; Cakmak, 2008; Liew *et al.*, 2010; Kihara *et al.*, 2017, 2020; Abdoli, 2020). In Zimbabwe, the adoption of improved soil fertility management (chemical and organic) resulted in a reduction on dietary Zn deficiency from 68-55 percent (Manzeke-Kangara *et al.*, 2021). This effect was estimated through EXANTE calculation applying data from a previous study which reported a two-fold greater concentration of plant-available soil Zn on fields receiving organic nutrient resources. The authors associated those increases in plant-available Zn in soil to larger grain Zn concentrations, averaging 25 mg/ kg in maize (Manzeke-Kangara *et al.*, 2019).

3. Impacts of misuse and overuse of nutrients on environmental pollution and climate change

3.1. Nutrient imbalances: a disturbance in the global nutrient budget

The evaluation of nutrient budgets, or the inputs and outputs of nutrients in a system, is a fundamental step toward soil fertility conservation and improved nutrient management. The differential between nutrient inputs and outputs, including productive outputs like crop harvest and losses to the environment, affects the nutrient stock of a system (Figure 7).

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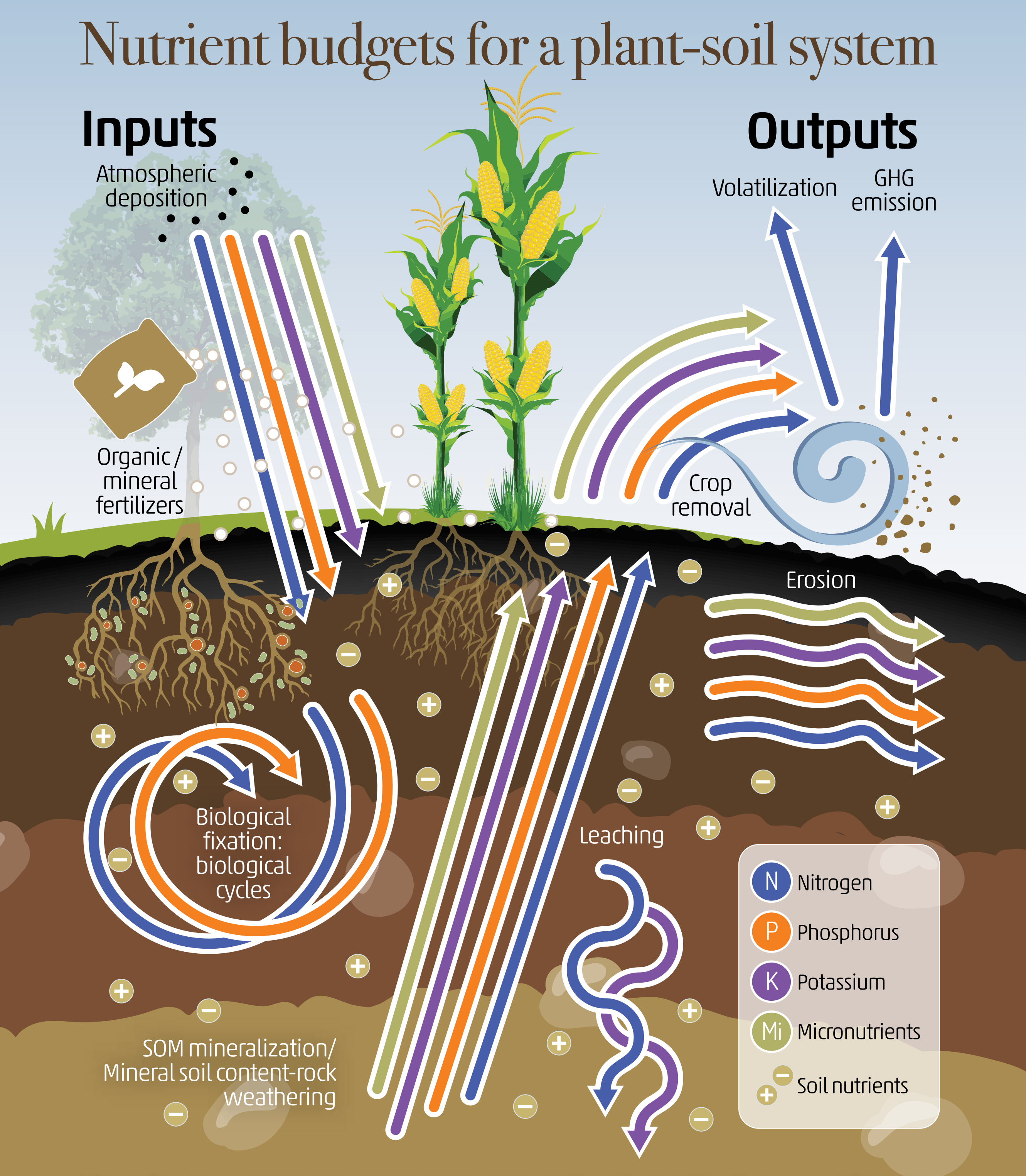
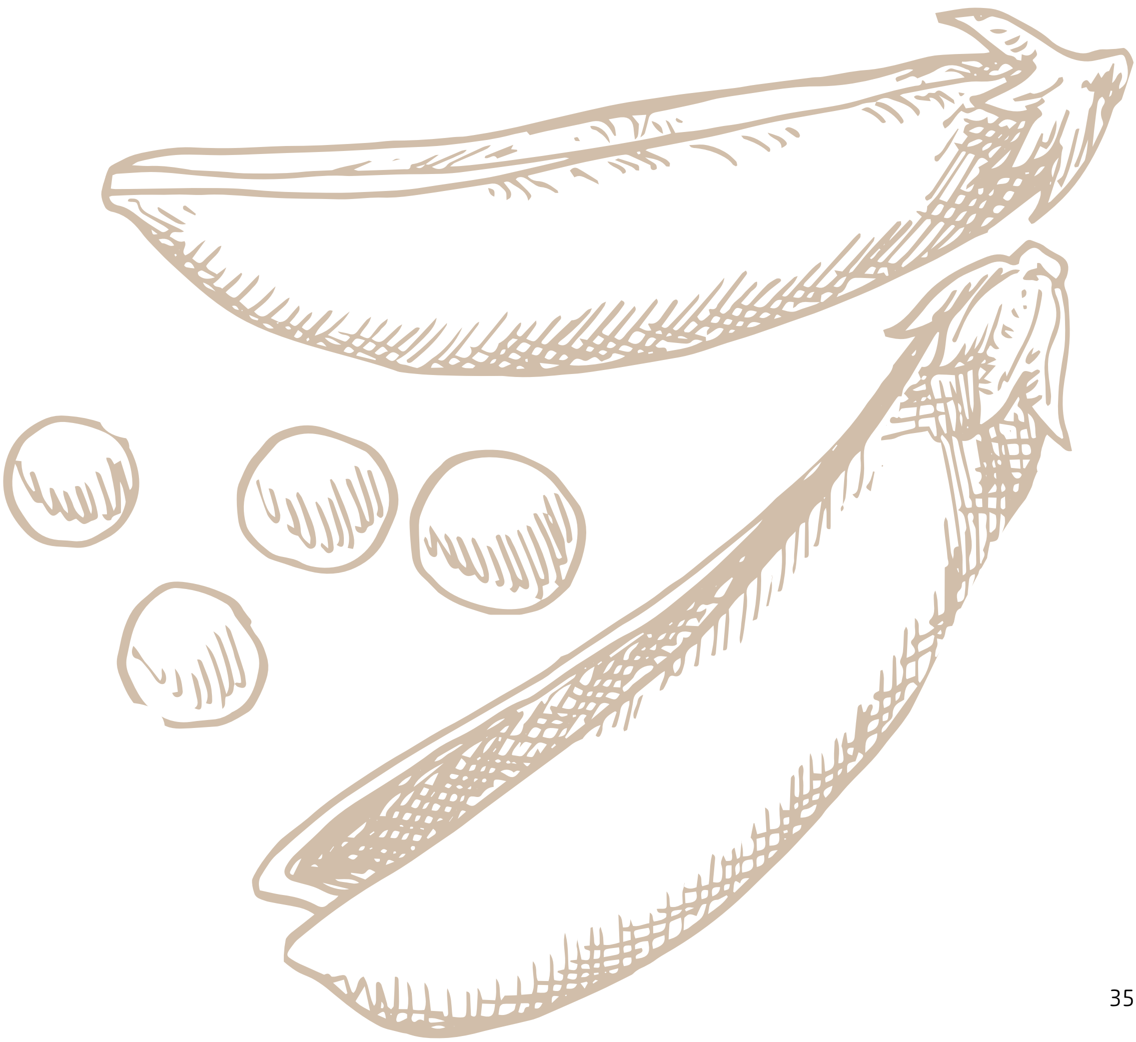
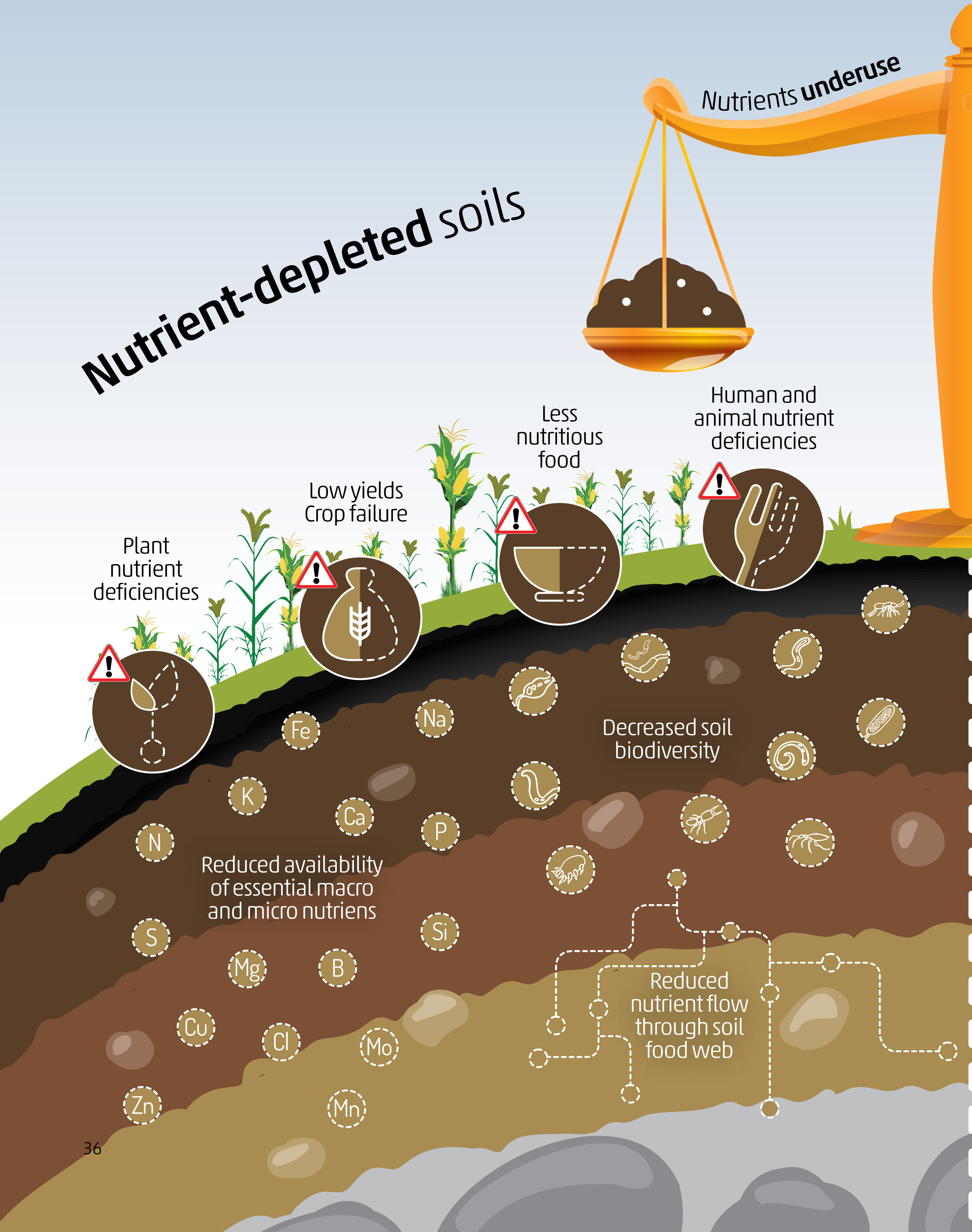


Figure 7. A schematic of nutrient budgets for a system. The left side of the figure shows the inputs, and the right side shows the outputs. The arrows indicate input and output fluxes. The outputs include those nutrients harvested and removed from the system, such as crops, straw, and animal products, which are usually economically valuable products. Different colours represent different nutrients

When the inputs (e.g. atmospheric deposition, fertilizers) are higher than the outputs (e.g. leaching, crop harvest) or vice versa, nutrient imbalances occur in the crop system. Soil nutrient imbalance is one of the main causes of soil degradation because it induces some soils to be nutrient depleted, losing their capacity to support crops, while others have such a high nutrient concentration that they represent a toxic environment to plants and animals (Figure 8). To boost crop yields, increasing levels of N, K, and P-containing fertilizers have been utilized in croplands since the end of World War II. These fertilizer applications have prevented soil nutrient depletion and, in some cases, even built-up soil nutrient stores. However, in many developing countries, including many sub-Saharan African, Latin American and Asian countries, soil N and P depletion remains a key problem for food security. Soil nutrient depletion does not occur exclusively because of macronutrients losses, as soil micronutrient abatement is still widespread. Despite the micronutrient deficiencies there are only a few global studies of the issue (Bouwman *et al.*, 2017; Vitousek *et al.*, 2009). Nutrient-deficient soils will produce nutrient-deficient plants, forages, and crops, causing animals and people suffering with nutrient deficiencies. Because of soil fertility loss, vegetables do not contain the same levels of vitamins and nutrients as they did 70 years ago, which poses a risk to human health (Colino, 2022).



Soil nutrient imbalances



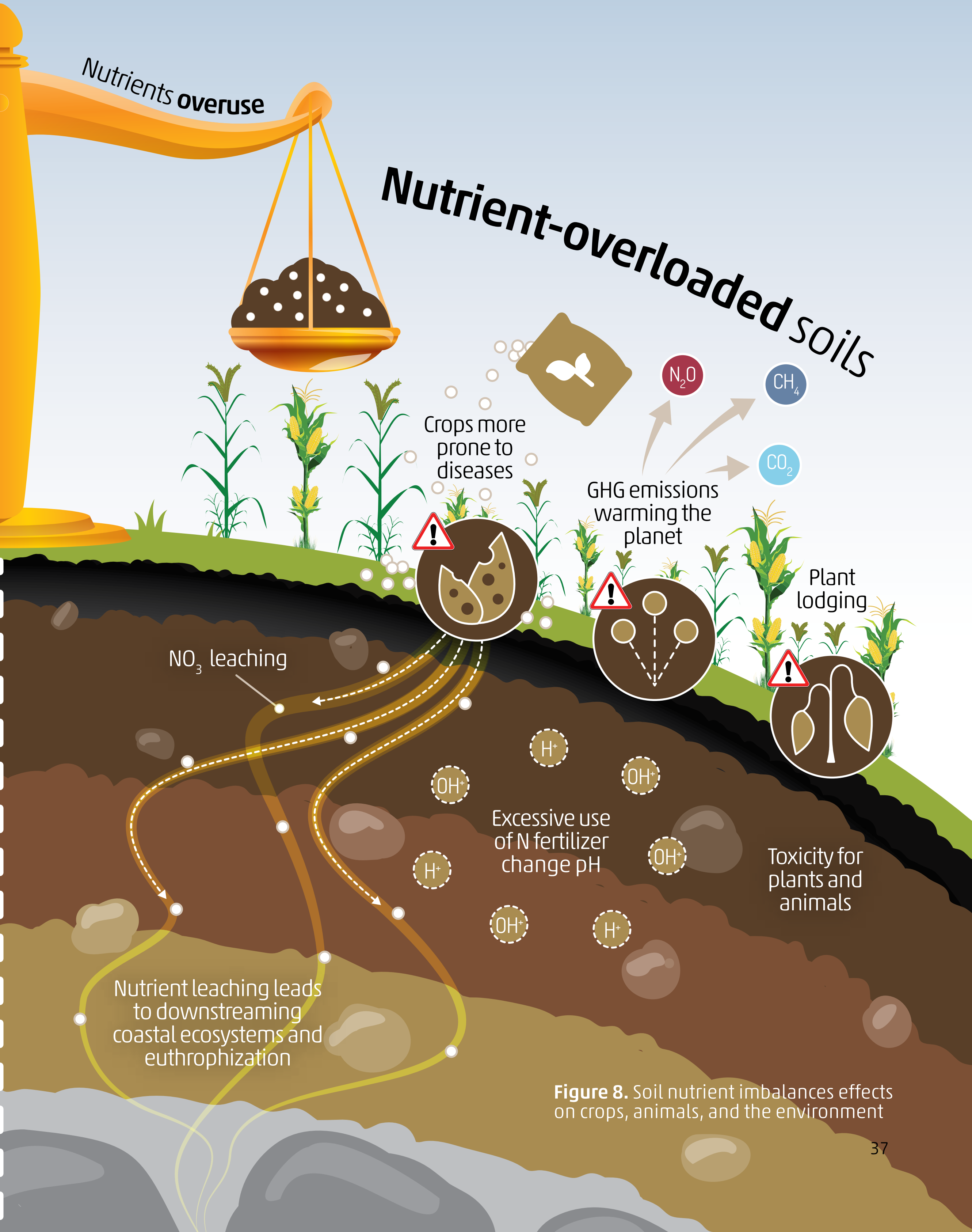


Figure 8. Soil nutrient imbalances effects on crops, animals, and the environment

3.2. Overuse and misuse of soil nutrients

Soils used for agriculture cover 38 percent of the Earth's ice-free surface and use 70 percent of freshwater for irrigation. Fertilizer use has increased by 500 percent in the past 50 years (Foley *et al.*, 2011). Fertilizer application is essential for intensive food production; however, its excessive use has generated problems of water, soil and atmospheric pollution and is also an important source of GHG that cause global warming (Erisman *et al.*, 2008).

The excessive use of fertilizers has detrimental effects that undermine the stability of ecosystems and the services they provide. Soil nutrients such as N and P are essential for crops, but once they leave the plant-soil system, they often become environmental polluting agents that are very difficult and expensive to retrieve (Figure 8). Globally, there is a scientific perspective that can be summarized in the phrase "too much of a good thing" (Sutton *et al.*, 2011), which expresses those fertilizers have brought benefits and are essential for human societies but are simultaneously threatening human and animal health.

There are global studies that show serious planetary effects of N and P cycles associated with excessive fertilizer use. Intensive, unsustainable agricultural activities have caused such intense environmental disturbances that they are undermining the stability of the Earth system. The biogeochemical cycles of N and P are included in the four planetary processes with the greatest anthropogenic impacts (Steffen *et al.*, 2015), mainly because of unsustainable agricultural activities. The amount of N and P that have been added to terrestrial and aquatic ecosystems is so large that both global cycles have been modified (Stevens, 2019; Elser and Bennett, 2011; Sutton *et al.*, 2020). This excessive use of fertilizers has contributed to exceeding the threshold of N entering the systems and has reached half of the threshold in the case of P (Röckstrom *et al.*, 2009; Steffen *et al.*, 2015).

Other studies show also global soil input increases in the N and P and low use efficiency of both macronutrients. For example, tile-drained fields lose on average nearly half of the N remaining after harvest but can lose as much as 85 percent (Greer and Pittelkow, 2018; Lory and Scharf, 2003). According to a global N and P fertilizer use budget (Lu and Tian, 2017), N and P fertilizer use rates per unit cropland area increased by approximately 8 times and 3 times, respectively, since the year 1961, and cropland expansion probably raises total fertilizer consumption even more. Increasing fertilizer use efficiency, and utilization of accumulated residual soil P has enabled a continuous increase in yields. However, the environmental risks associated with the legacy of excessive nutrient mobilization caused severe environmental pollution and human health problems in the 1970s and 1980s (Bouwman *et al.*, 2017).

Inequalities in fertilizer use are part of the complexity of the problem of fertilizer misuse. Most of the use of available synthetic fertilizer is concentrated in 50 countries while the rest of the countries have restricted access, restraining crop production. Fertilizer use in high-income countries has not decreased in recent years (except in European countries). Hotspots of agricultural N fertilizer application shifted from the United States and western Europe in the 1960s to eastern Asia in the early 21st century, while P fertilizer input showed a similar pattern with an additional current hotspot in Brazil. A global increase in fertilizer N/P ratio by 0.8 g N/g P per decade occurred during 1961–2013, which may have an important global implication for agroecosystem functions in the long run (Lu and Tian, 2017). In the last decades farmers in developed countries - also including China and India -, have accumulated a large store of residual P in crop soils which might be eventually available for plant uptake.

Concerns have been raised regarding the duration of reserves of this element, which are limited. Unlike N, P cannot be produced synthetically. P used in the manufacture of fertilizers is obtained from mines and is a non-renewable natural resource. The largest reserves of P are concentrated in five countries and studies predict that these could be reduced in 50-100 years, with extraction peaking in 2030 (Cordell, Drangert and White, 2009). However, more recent research suggests that the magnitude of reserves is uncertain and comprehensive assessment methods are needed to better predict the state of mineral reserves (Scholz and Wellmer, 2013). These findings are consistent with a reevaluation of global phosphate reserves and the advances enabling higher extraction and processing efficiency, which is an indicator that P reserves have the possibility of lasting much longer. So far, there is no known chemical or technological substitute for P in agricultural ecosystems, which places us in a dependence on natural reserves of this element and forces us to optimize its use.

3.2.1. Status of soil, water, and air pollution derived from the overuse or misuse of fertilizers.

Fertilizer overuse can lead to serious impacts on soils, freshwater, groundwater, air and biodiversity in terrestrial and aquatic systems (Galloway *et al.*, 2003). Continuous cropping and misuse, and overuse of chemical fertilizers can diminish SOM content very rapidly, leading to soil structural decline and soil acidification, thereby affecting beneficial organisms, stunting plant growth, causing variations in the soil solution pH, pest proliferation and even contributing to the undesirable release of GHG (Figure 8).

As far as soils are concerned, N fertilizer overuse induces changes in soil pH (in general, acidification), and thus in the soil microbes (Hickman *et al.*, 2020). The lower biological activity ends up affecting the SOM cycling, biological N fixation and various physical properties associated with water supply and air exchange. The excessive use of N fertilizers increases NO_3^- leaching and surface runoff, seriously threatening human health and polluting the environment (Wang and Li, 2019). Approximately half of the N applied in fertilizers is lost to the surrounding environment in the form of Nr (Delgado and Follet, 2010). Nr in the form of NO_3^- moves very easily in water and this causes it to disperse easily and to travel long distances with respect to the place where it was originally applied, which is known as an N cascade (Galloway *et al.*, 2003). Nitrate ions are prone to leaching because the negative charge prevents them from being adsorbed onto the negatively charged colloids that dominate most soils. NO_3^- leaching from farming systems can cause:

- Groundwater contamination, since NO_3^- is frequently detected as a pollutant in drinking water and in groundwater (Weil and Brady, 2017).
- Deterioration of water quality leading to severe and difficult to reverse problems including eutrophication, hypoxia, biological invasions and biodiversity loss in aquatic environments (Schlesinger, 2009).

- Biodiversity destabilization and species invasion. An example of this is the massive *Sargassum* blooms in the Atlantic Ocean, due to (among other causes) the higher nutrient supply and discharge from farming systems in West Africa and the Amazon River resulting in impacts on distant areas (Wang *et al.*, 2019).
- Anthropogenic acidification of soils, since high levels of N fertilization can drive both, direct and indirect soil acidification (Guo *et al.*, 2010).

The excessive applications of N through fertilizers also contaminate the air. In addition to their contribution to climate change, once the NOx gases reach the atmosphere, they affect the environment in other ways including (Galloway *et al.* 2003):

- NOx gases react with volatile organic pollutants to form ground-level ozone (O_3), a major air pollutant in the photochemical smog affecting urban areas;
- NO and N_2O contribute to the formation of nitric acid (HNO_3), one of the principal components of acid rain;
- Destruction of ozone (O_3) in the stratosphere, which is a gas that helps to protect our planet from ultraviolet solar radiation through N_2O reactions. The O_3 protective layer depletion is associated with annually growing cases of skin cancer.

Since the middle of the 20th century, the input of P into terrestrial ecosystems has quadrupled (Falkowski *et al.*, 2000), creating a unidirectional flow of this element from rocks extracted from mines to crops (Elser and Bennet, 2011). The main impacts that human activities have had on the global P cycle include its extraction from mines and the global redistribution of P in the form of fertilizers, animal feed and detergents (Bennett and Schipanski, 2013). Erosion and land-use change, as well as the movement of P from terrestrial to aquatic ecosystems through sewage sludge discharge and septic tank leakage also contribute to modifying the P cycle. Annually, these human activities promote the anthropogenic input to soils of 23 Tg P in the form of fertilizers and animal feed, exceeding the natural input of 15-20 Tg P that occurs through weathering of parent material (MacDonald *et al.*, 2011).

Progress has been made in nature-based solutions to increase the solubility of P in soils, such as the use of soil organisms and algae, which at the same time have a purifying effect on eutrophication (Mau *et al.*, 2021). The path towards reducing eutrophication because of N and P inputs to aquatic ecosystems includes several innovative technologies, such as the use of biological waste to produce organic fertilizers (Chojnacka, Moustakas and Witek-Krowiak, 2020), aquaculture input (Deng *et al.*, 2021) or the generation of biofuels from algae (Behera *et al.*, 2015). These novel technologies indicate that nutrient use can truly be a closed loop towards a circular economy.

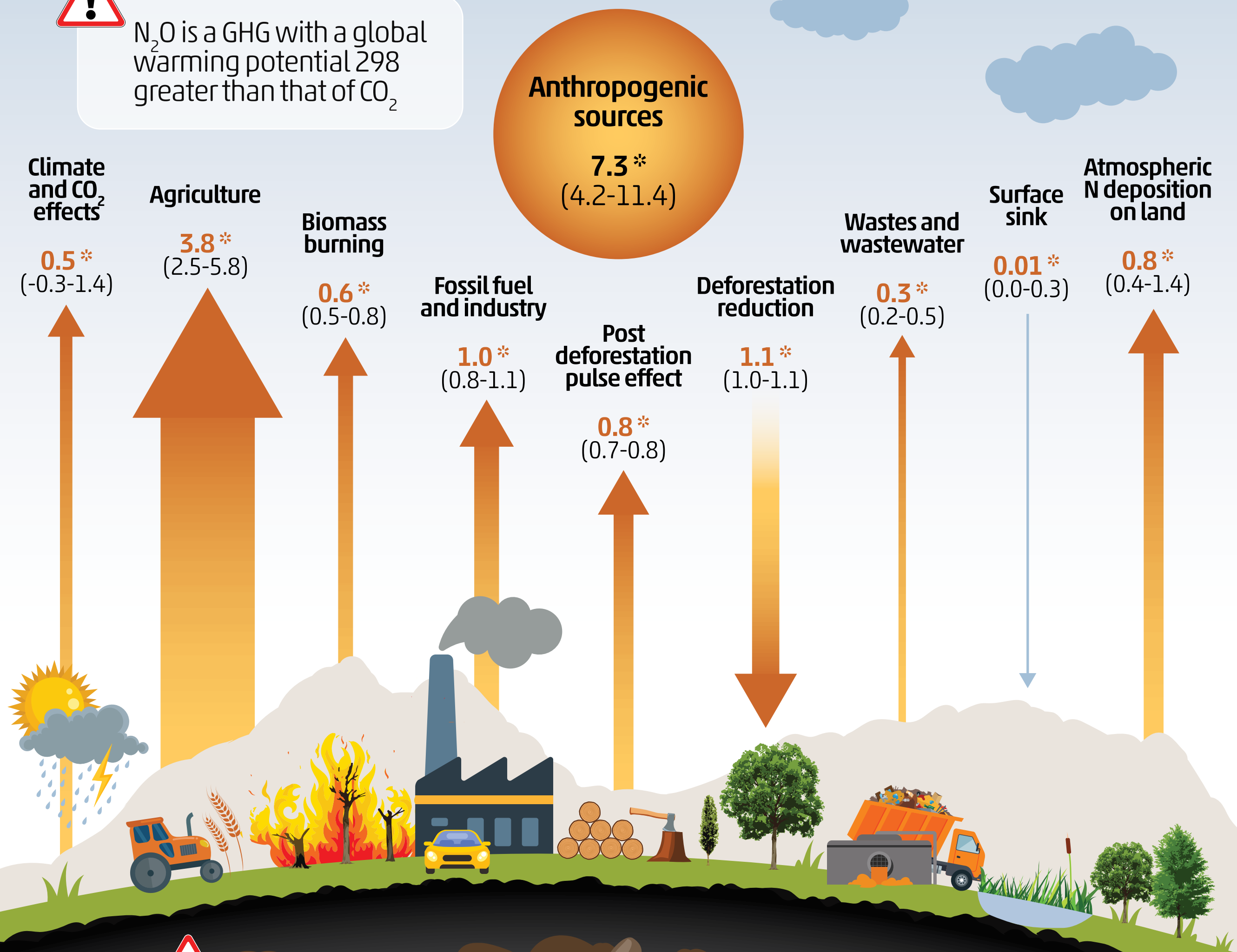
3.3. The impact of overuse and misuse of fertilizers on climate change.

Nitrogen fertilizers are a major source of N inputs to managed agricultural systems, contributing significantly to direct and indirect N_2O emissions from managed agricultural soils (Figure 9). N_2O is a GHG that mostly originates in agricultural soils. Although N_2O occurs at lower concentrations in atmosphere compared to CO_2, it has a global warming potential 298 larger than that of CO_2. That implies a huge capacity to trap infrared energy radiated from Earth, thus contributing to global warming (IPCC, 2021). Planetary anthropogenic N_2O emissions have reached 7.3 Tg yr^{-1} (1 Tg= 10^{12}g). Farming activities are the main source of these emissions which represents approximately half of the anthropogenic agricultural emissions (Figure 9), with N additions to croplands the main driver (Tian *et al.*, 2020). Synthetic N fertilizers are a major source of N entering managed soils and then being released as N_2O emissions. However, the misuse and overuse of organic fertilizers, urine and dung deposited by grazing livestock, organic crop residues and SOM decomposition can also significantly contribute to N_2O emissions.

The emissions of N_2O from croplands can act synergistically with other soil processes relevant to climate change mitigation such as soil organic carbon (SOC) sequestration. According to a meta-analysis (Guenet *et al.*, 2021) climate change mitigation induced by increased SOC storage is generally overestimated if associated N_2O emissions are not considered. Because of the high global warming potential of N_2O even small changes in the emissions of this GHG could offset SOC increments and atmospheric CO_2 mitigation (FAO, 2021). There are reports indicating that N_2O emissions offset between 56 – 61 percent of the CO_2 reduction associated with C sequestration in no-till crops (Grandy and Robertson, 2006).

Anthropogenic global N_2O emissions on land

N_2O is a GHG with a global warming potential 298 greater than that of CO_2



Global human-induced emissions of N_2O amount to 7.3 Tg /yr (1 Tg= 10^{12}g), with agriculture being the largest source.
Agriculture accounts for 52 percent of anthropogenic emissions, which are dominated by N additions to croplands

* Teragrams per year
(1 Teragram = 10^{12} g)

Figure 9. Diagram illustrating the anthropogenic sources of N_2O emissions on land
Source: Adapted from Tian, H., Xu, R., Canadell, J.G., Thompson, R.L., Winiwarter, W., Suntharalingam, P., Davidson, E.A. *et al.* 2020. A comprehensive quantification of global nitrous oxide sources and sinks. Nature, 586(7828): 248–256. https://doi.org/10.1038/s41586-020-2780-0

3.4. The quality of fertilizers and its role in food safety, human health, and pollution.

The risks of the use of fertilizers (mineral and organic) for human and environmental health depend largely on the origin of the raw material with which these fertilizers are produced. In the case of mineral fertilizers, the presence of polluting elements in the parent material used for fertilizers production is associated with the presence of natural and anthropogenic polluting elements in the mining area. This risk typically appears in some mineral sources of P, which comes from phosphate rock that can be rich in Cd and other pollutants (Khan *et al.*, 2018).

During the phosphate rocks extraction in the mines the mobilization of radionuclides and trace elements occurs, including As, Cd, Cr, lead (Pb), mercury (Hg), fluorine (Fl), uranium (U), radium (Ra) and thorium (Th) (Reta *et al.*, 2018). These harmful compounds are transferred to soils through phosphate fertilizer and then to plants and the food chain (Pan *et al.*, 2010). Other risks are determined by the characteristics of the soil at the application site, since the greater risk that acid soils generally imply, due to the increased bioavailability of some trace elements (Fe, Mn, Cu, Zn among others) and heavy metals (Figure 10). In addition to soils characteristics, it has been observed that sustained phosphate fertilizer applications overtime increase Cu, Zn and Cd concentrations in soils. The Cd content of phosphate rocks is variable, and it is associated with the rock type they derive from, with sedimentary deposits significantly higher with a concentration of up to 150 mg/g compared to igneous phosphate rock with a concentration of 2 mg/kg. The sedimentary deposits account for 85 percent of global P fertilizer (Van Kauwenbergh, 2010), which suggests that innovations for increasing the availability of this element on crop soils should be a priority.

Cadmium life cycle in fertilizers and impacts on human health

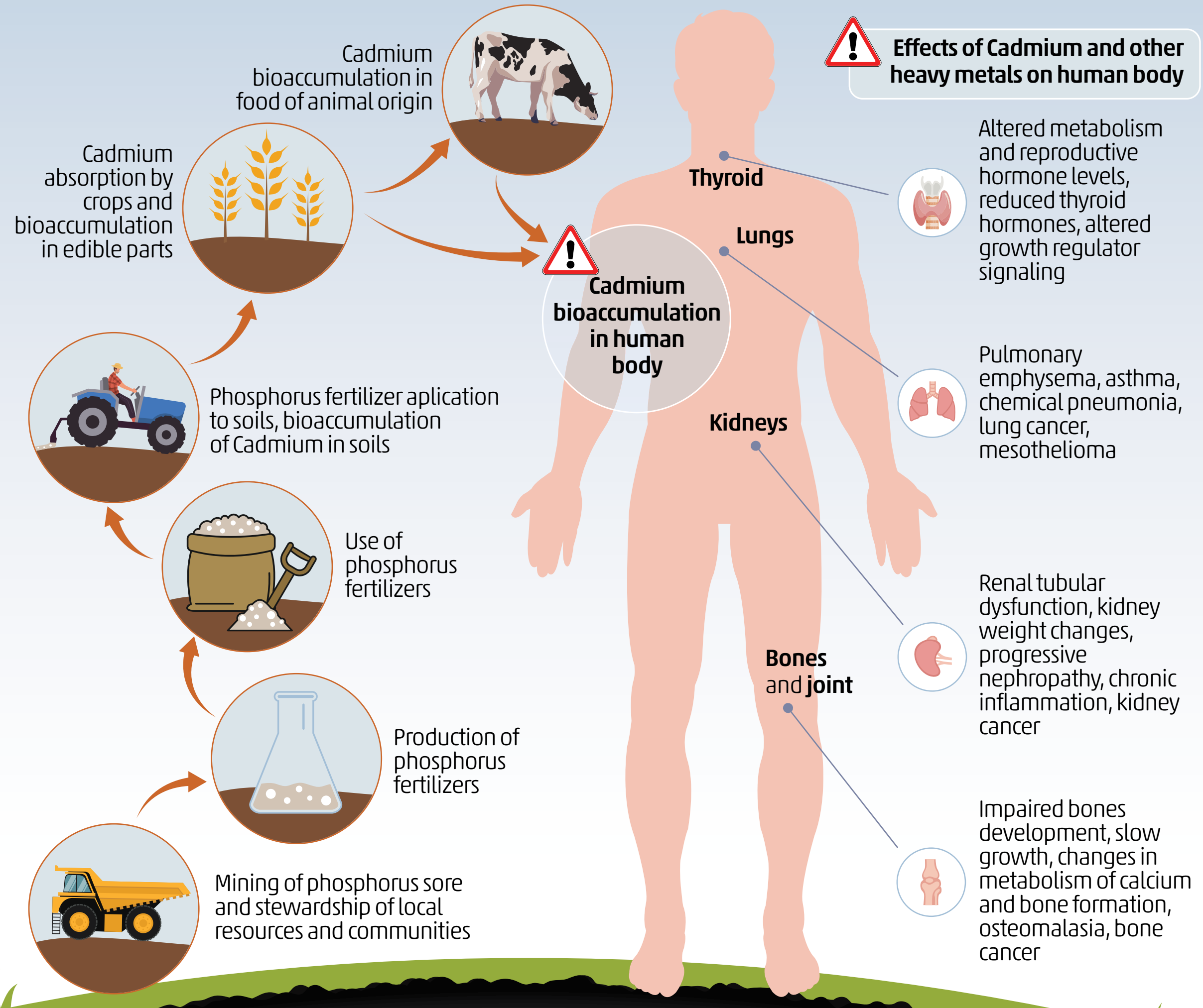


Figure 10. Life cycle of Cadmium in P fertilizers and soils. Cadmium enters soils and bioaccumulates until it reaches the human body, affecting its health, especially the functions of the thyroid, kidneys, and bone system

Source: Adapted from Opera Research, 2021. Cadmium limits in phosphorous fertilizers. https://operaresearch.eu/wp-content/uploads/2019/11/EN_WEB_Cadmium-threshold-in-phosphorous-fertilizers.pdf
FAO and UNEP. 2021. Global assessment of soil pollution: Summary for policymakers. Rome, Italy, FAO. 84 pp. https://doi.org/10.4060/cb4827en

The use of organic fertilizers is not risk-free, especially when they come from industrial, biological, or household waste, or are derived from sewage sludge. It is recommended to analyse these types of fertilizers for the presence of contaminants with a risk of transfer to humans, or the food chain. The most common pollutants are heavy metals such as Pb, Cr, Cd, and Hg, organic chemicals, such as those derived from the oil, refinery and pesticide industries, or biological ones such as highly persistent pathogens in soil and water. Any of these pollutants is (or should be) regulated in the different countries, with clearly established criteria to separate fertilizers or products suitable for application, those applicable with certain restrictions on use, or those that, given their level of risk, are classified directly as hazardous waste, and must be taken to a final disposal site (Mayer and Wang, 2018). Chromium can be present in organic and mineral fertilizers, organic amendments and limestone. The major contents are found in fertilizers consisting of tanning residues (100-99 000 mg/kg), sewage sludges (8-40 600 mg/kg), municipal solid waste (MSW) composts (1.8-5 000 mg/kg), and phosphatic fertilizers (66-245 mg/kg) (Soler Rovira *et al.*, 1997).

The Fertilizer Code (FAO, 2019c) is a useful instrument that provides recommendations related with the use of recycled nutrient sources, and storing, handling, and safety. The Fertilizer Code provides a locally adaptable framework and a voluntary set of practices to serve the different stakeholders directly or indirectly involved with fertilizers, since the needs are different among stakeholders (Figure 11). In the area of reuse and recycling of nutrients, the Fertilizer Code recommendations include the encouragement of scientific research and technology development for the decontamination of sewage sludge and other recycled sources. It is also essential to facilitate the exchange of knowledge and information on the use and recycling of nutrients for agricultural use among key stakeholders such as government, industry, academia, land managers and farmers.

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The International Code of Conduct for the Sustainable Use and Management of Fertilizers

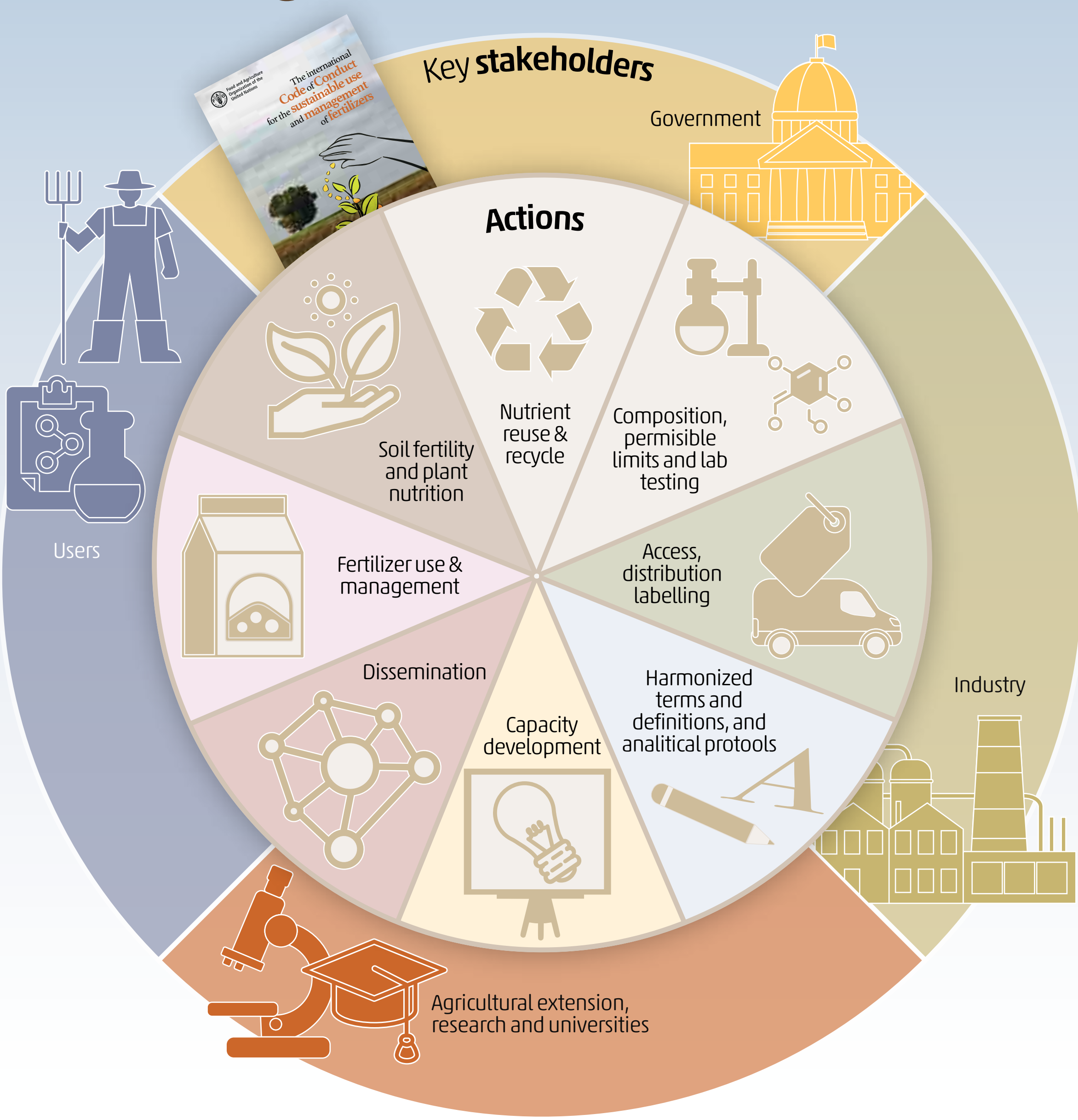


Figure 11. The International Code of Conduct for the Sustainable Use and Management of Fertilizers (Fertilizer Code) as a crosscutting approach for a complex problem. The Fertilizer Code is an instrument that considers recommendations for direct and indirect stakeholders involved in the use of fertilizers

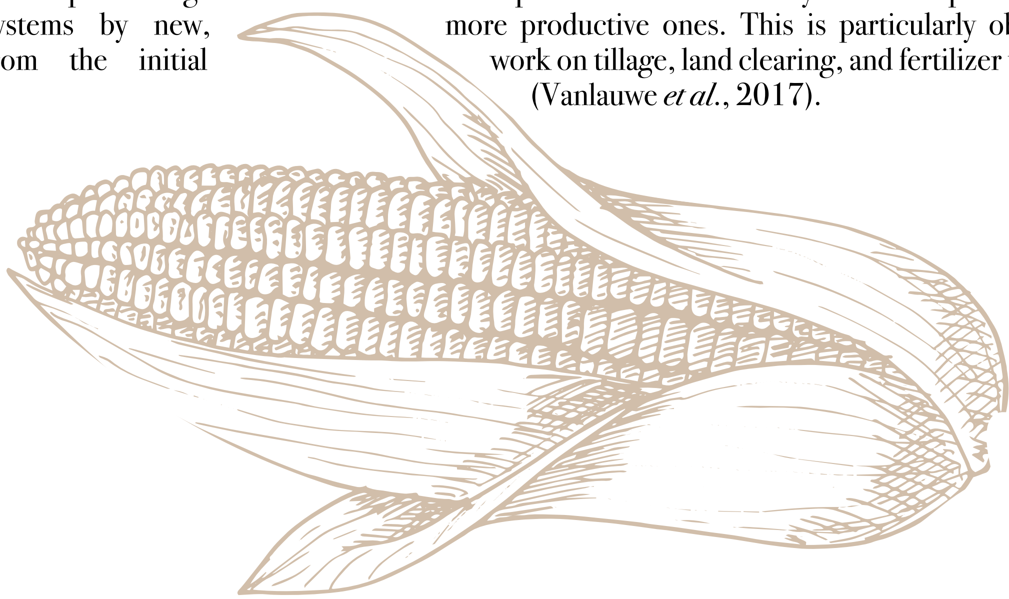
Considering the severe adverse effects that poor fertilizer quality can have on soil, animal and human health and the environment, the evaluation of fertilizer quality is a priority issue to achieve SSM. The quality of fertilizers and their bioavailability ensures that fertilizers and recycled nutrients are compliant with quality and safety standards. Fertilizer quality should be assessed and monitored at national level. The GSP has launched a global effort to assess the quality of fertilizers through the International Network on Fertilizer Analysis (INFA), which is focused on enhancing the capacity of laboratories in fertilizer analysis laboratories and improving quality standards to support a more sustainable use of fertilizers.

3.5. Alternatives to improve nutrient use efficiency

3.5.1 Integrated soil fertility management

Integrated soil fertility management (ISFM) is an approach to improve crop yields, while preserving sustainable and long-term soil fertility through the combined judicious use of fertilizers, recycled organic resources, responsive crop varieties and improved agronomic practices. Together, these measures minimize nutrient losses and improve the nutrient-use efficiency of crops. As defined operationally by Vanlauwe *et al.* (2015) ISFM includes a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles. The ISFM approach has been mainly applied in sub-Saharan Africa, where there is the need for improved agronomic practices to combine these various interventions over time and space.

The vision and content of the technology development research over 50 years in sub-Saharan Africa are illustrated in Figure 12. It indicates the approximate periods of development of different technologies, their evaluation and validation, and the assessment of uptake, adoption and impact. Its goal was the replacement of assumedly outdated production systems by new, more productive ones. This is particularly obvious from the initial work on tillage, land clearing, and fertilizer use (Vanlauwe *et al.*, 2017).



Evolution of the technologies towards integrated soil fertility management

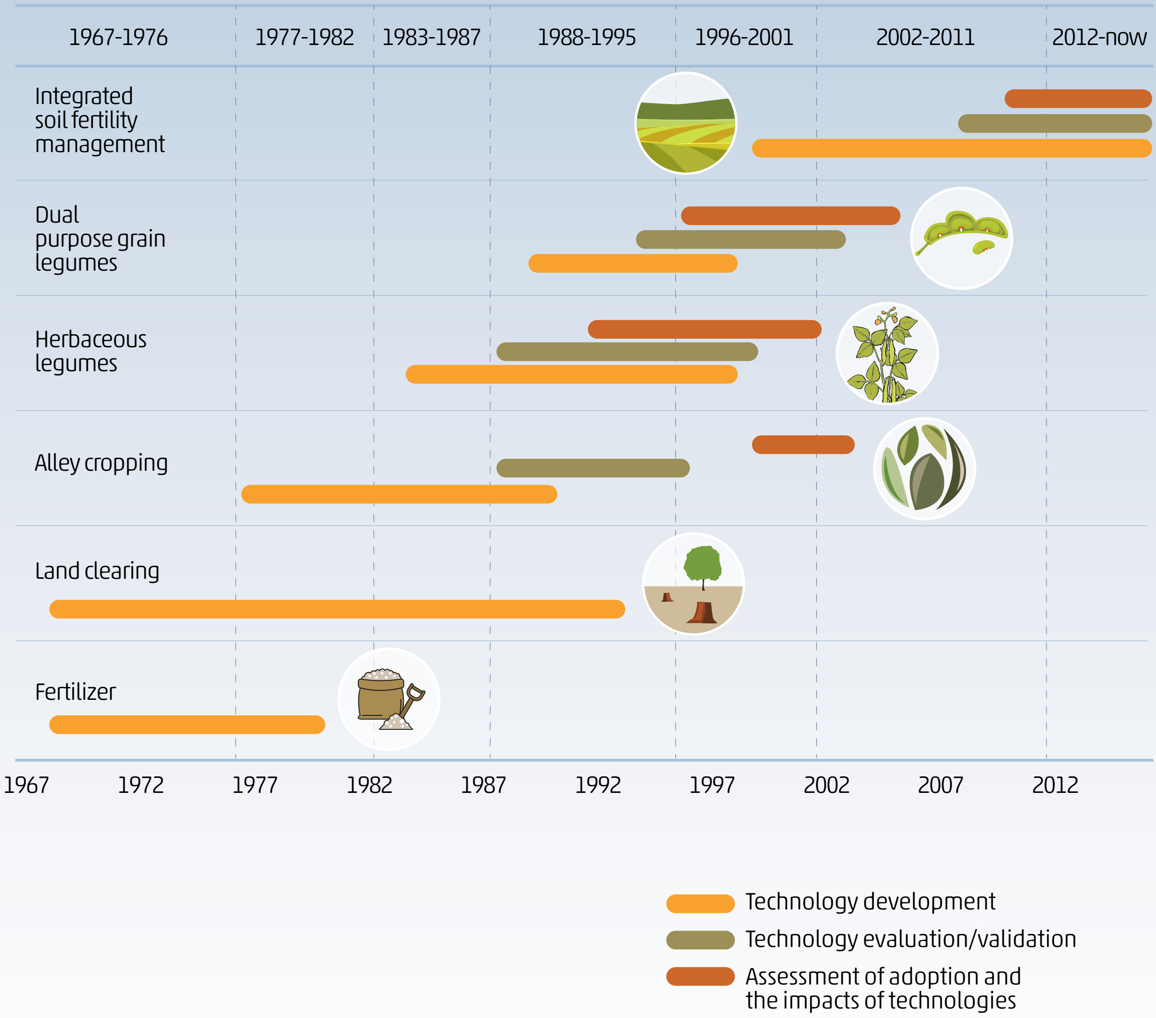


Figure 12. Historical trends in the technologies and practices prioritized by associated soil fertility research and programs at the International Institute of Tropical Agriculture (IITA)

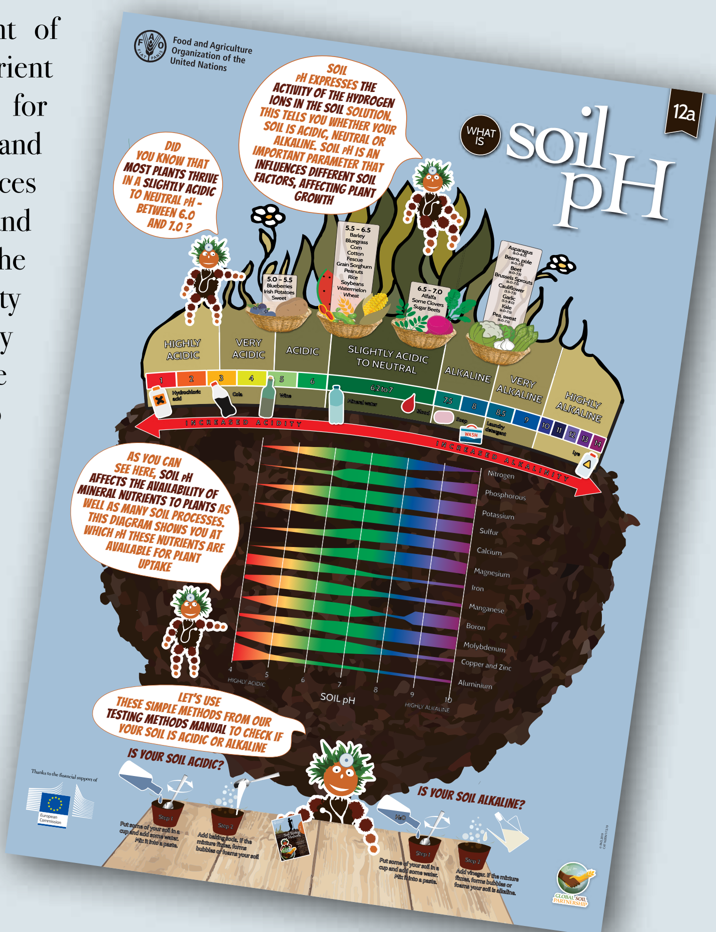
Source: Adapted from Vanlauwe, B., AbdelGadir, A.H., Adewopo, J., Adjei-Nsiah, S., Ampadu-Boakye, T., Asare, R., Baijukya, F. *et al.* 2017. Looking back and moving forward: 50 years of soil and soil fertility management research in sub-Saharan Africa. International Journal of Agricultural Sustainability, 15(6): 613–631. https://doi.org/10.1080/14735903.2017.1393038.

Soil management initiatives should focus on providing holistic solutions covering both biophysical and socio-economic aspects along the entire value chain and creating an enabling environment for adoption. A broader view of soil fertility improvement, including the access to inorganic fertilizers, using all available options including both inorganic and organic sources of nutrients, and farming system approaches are highly recommended (Stewart *et al.*, 2020).

A fundamental component for the implementation of strategies focused on ISFM is capacity building, aimed directly to farmers. An example of capacity building approaches is the Global Soil Doctors program which counts with specific modules targeted at training farmers on the sustainable management of soil nutrients and on good practices in relation to fertilizer use (Box 1). This and other capacity building programs are key to rise consciousness on farmers on the importance of physical, chemical, and biological soil properties for the determination of the nutrient availability and cycling (including micro-nutrients) and thus to assess the fertilizer needs.

Boosting farmers capacity on sustainable soil nutrient management: the Global Soil Doctors Program

The maintenance and enhancement of soil fertility through sustainable nutrient management is of great importance for achieving food security for present and future generations. However, practices aiming at increasing soil fertility and crop production should consider the preservation of soil health as a priority which has been often overlooked by policy makers and end users, the farmers. It is therefore essential to carry out specific actions to raise awareness that degraded soils provide limited access to nutrients for plant uptake preventing crops response to nutrient additions and causing soil nutrient losses.



The Global Soil Doctors Program is farmer- to-farmer training initiative launched in 2020 that aims to build the capacity of farmers on the principles and practices of sustainable soil management using targeted educational tools. The program is based on the Farmer Field Schools (FFSs) approach (FAO, 2021) and implemented to emphasize the role of sustainable soil management practices in reversing the increasing trend of soil degradation. Specific modules were developed to address the issues of nutrient management and fertility, each one including theoretical and practical sessions.

The educational material consists in a series of posters that explain the importance of soil physical chemical and biological components for enhancing nutrients availability. A series of field exercises guide the farmer for the qualitative assessment of soil conditions using simple protocols and common tools. The final evaluation of the overall soil conditions will serve as a baseline for the practical recommendation provided at the end of each module.

The Global Soil Doctors Program in action: Bolivia as a case study

The implementation of the module on soil fertility in Bolivia started in March 2022 to support the activity of technicians and producers from Bolivian organizations and improve the capacity of local farmers on management practices applicable in agroforestry. In the module 1, emphasis was given to the role of pH and soil SOM in regulating nutrients supply. As a matter of fact, variations in soil pH and SOM can greatly influence the soil fertility status. A specific field exercise was developed to understand the factors limiting nutrients availability, counting also on the support of available soil laboratory analyses. The program was enriched by local examples and personal experiences of the Soil Doctors trainers that actively contributed to the implementation at the country level. A second module will be developed to address the need of a more judicious use of fertilizers owing to the capacity of healthy soils balance nutrient supply with crop demand the natural ecosystem balance to avoid nutrient deficiency or excess.

3.5.2. Nature-based solutions: soil microorganisms to reduce externalities of fertilizer use

Nature-based solutions (NbS) are defined as actions to protect, sustainably manage, and restore natural or modified ecosystems and that address societal challenges effectively and adaptively, simultaneously providing benefits for human well-being and biodiversity. NbS mimic natural processes relying on ecosystem functioning to ensure food and livelihood security, healthier diets and more inclusive rural economies (Arnés-García and Santivañez, 2021). Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient, and systemic interventions. NbS have been conceived to benefit biodiversity and support the delivery of a range of ecosystem services.

NbS can be practiced to improve soil fertility and soil nutrient content through different approaches including the capture of atmospheric N by biological nitrogen fixation (BNF). Currently symbiotic plants such as legumes are utilized but at least thirteen genera belonging to the prokaryote group are known to fix N (Figure 13). BNF is one of the main alternatives to overcome the overuse of synthetic N fertilizers. Indeed, more than 60 percent of the fixed N on Earth results from BNF. Therefore, optimizing BNF in agriculture is urgent to help meet the demand of the food production needs for the growing world population (Soumare *et al.*, 2020). NbS also include the solubilization of precipitated forms of P to increase its availability for plants by harnessing soil biodiversity; the use of microorganisms to recover contaminated soils and waters because of the excessive use of fertilizers and manures, or those carrying hazardous elements (environmental contamination); and mitigation of climate change through the use of biofertilizers.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Nitrogen fixing organisms

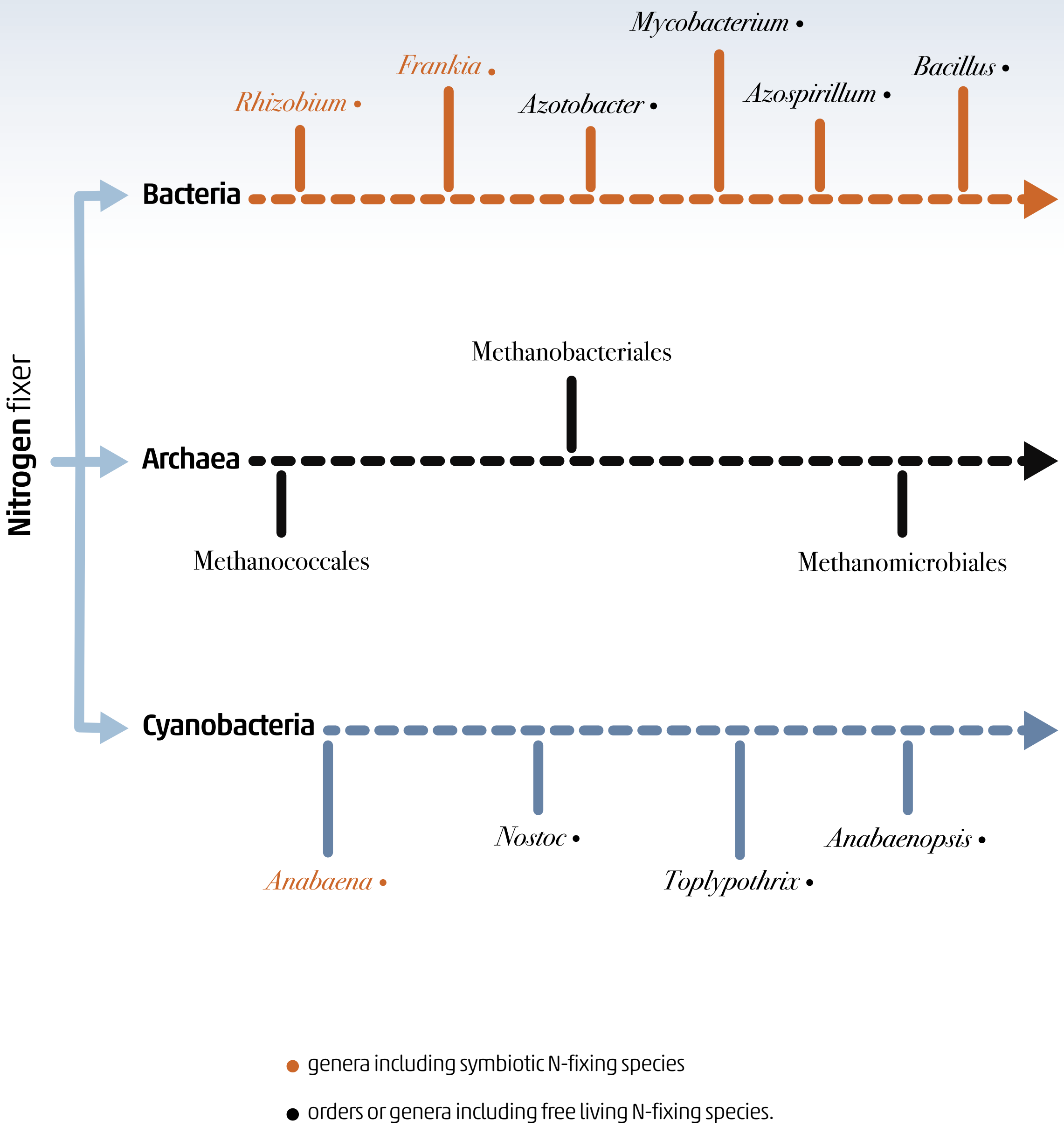


Figure 13. Different groups of N-fixing organisms including some examples of the main genera. In red: Symbiotic N-fixing species; orders or genera (in italics) including free living N-fixing species depicted in black

Source: Adapted from Soumare, A., Diedhiou, A.G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S. & Kouisni, L. 2020. Exploiting biological nitrogen fixation: A route towards a sustainable agriculture. Plants, 9(8): 1011. https://doi.org/10.3390/plants9081011.

For more examples about applications of soil biodiversity on enhancing soil fertility and improving soil health see the State of Knowledge on Soil Biodiversity (FAO, ITPS, GSBI, CBD and EC, 2020) which includes a comprehensive review of the utility of soil microorganisms in the development of different strategies to improve and recover soil fertility.

Remediation of polluted agricultural soils using biological methods has been adopted successfully. Phytoremediation has proven to be a promising alternative to conventional approaches as it is cost effective, environmentally friendly and aesthetically pleasing. To date, based on the natural ability of extraction, approximately 500 taxa have been identified as hyperaccumulators of one or more metals (Li *et al.*, 2019). Strategies based on Combined Phytoremediation and Food Production (CPFP) may be appropriate options for most pollutants in virtually all climatic or socioeconomic contexts, but several challenges need to be surpassed. The challenges include remediation technological issues such as undeveloped post-harvest technology and inadequate soil governance (Haller and Jonsson, 2020).

In the case of environmental contamination with persistent organic pollutants (POP), bioremediation is a key to eliminate these harmful pollutants from the environment. Scientific knowledge upon microbial interactions with individual pollutants over the past decades has helped to abate environmental pollution. Traditional bioremediation approaches have limitations for their applications; hence, it is essential to discover new bioremediation approaches with biotechnological interventions for best results (Mishra *et al.*, 2021). For a wider view on soil contamination, impacts and solutions, see the Global Assessment on Soil Pollution (FAO and UNEP, 2021).

One of the most relevant NBS strategies to sustainably increase soil nutrient content is the use of biofertilizers, especially in view of rapidly decreasing P stocks and the need to increase NUE (Schütz *et al.*, 2018). According to the Fertilizer Code, a biofertilizer is a broad term used for products containing living or dormant micro-organisms such as bacteria, fungi, actinomycetes and algae, alone or in combination, which on application help in fixing atmospheric N or solubilize/ mobilize soil nutrients (FAO, 2019c). Biofertilizers increase particularly the availability of P, K, and other nutrients. Fungi and plant roots establish symbiotic relationships called mycorrhizae (Sattar *et al.*, 2019; Bhatt *et al.*, 2021) which increase the growth, yield, and absorption of nutrients in the plant mostly by increasing the effective absorptive area of the roots by formation of an extensive extra-radical hyphal network (Etesami, 2020). Based on a meta-analysis that quantified the benefits of biofertilizers in terms of yield increase, N and P use efficiency from 171 peer reviewed publications, Schütz and collaborators (2018) found that yield response due to biofertilizer application was generally small at low soil P levels; efficacy increased along higher soil P levels in the order arbuscular mycorrhizal fungi (AMF), P solubilizers, and N fixers. The analysis also revealed that the success of inoculation with AMF was greater at low organic matter content and at neutral pH. In addition to physical and chemical soil properties, climatic conditions seem to play a relevant role since the biofertilizer performance was better in dry climates over other climatic regions (Schütz *et al.*, 2018). The application of biofertilizers is shown to be effective in improving not only soil nutrients but also soil health by direct suppression of pathogens (for example the *Fusarium* disease) or antagonistic interactions via modification of the indigenous microbial community (Zhang *et al.*, 2020). While the importance of microbes, and host plant is undeniable for the success in the biofertilizer use, it has also been emphasized the relevance of soil properties and management, particularly SSM and SOM content (Tosi *et al.*, 2020) because of the strong influence of physical and chemical properties on soil microbes. Among the most important challenges to the successful use of biofertilizers that are related to the soil are the negative biological interactions such as competition with the native microbiome, the high variability of physico-chemical conditions (pH, SOM, nutrient status), and the interaction with other agricultural practices (pesticide and herbicides application), represent a challenge for the successful performance of fertilizers (Mitter *et al.*, 2021).

Biofertilizers commercialization has significantly increased. The global market for biofertilizers accounted for USD 1 254.2 million in 2016, and it is expected to increase 13 percent between 2017 to 2025. According to the Global Biofertilizers Market, Europe and Latin America are currently the top consumers of biofertilizers followed by China and India, because in many countries from these regions there are stringent regulations imposed on chemical fertilizers. In the worldwide market for biofertilizers, N fixing is largely predominant (79 percent). In contrast, the phosphate solubilizing biofertilizers barely accounts for 14 percent of the total (Soumare *et al.*, 2020).

Since P reserves are finite, fertilizers prices have increased, and the possibility of acquiring P fertilizers is limited for many farmers, biofertilizers play a leading role especially in the case of P and represent an advantageous and environmentally friendly approach to increase the solubilization of this element in the soil solution (Kalayu, 2019). Phosphate solubilizing microorganisms can transform non-soluble forms of organic and inorganic P by hydrolysis. Soil bacteria and fungi P-solubilizing microorganisms account for up to 50 percent and < 1 percent, respectively, of the total microbial population (Chen, Lin and Huang, 2006; Khan *et al.*, 2009). Although research associated with P-solubilizing organisms is extensive, a leap towards scaling up production and commercialization at more affordable prices is needed. It should also be considered that biofertilizers do not function in the same way as their synthetic counterparts, so work still needs to be done on the development of suitable formulations, rate recommendations, and applications.

3.5.3. Technology-oriented solutions for fertilizer optimization

Technologically oriented solutions for better management of nutrients and fertilization include a wide range of options including the use of sensors, variable rate applicators, nitrification inhibitors, modelling, etc. These options range from a better diagnosis of deficiencies with sensors, a more efficient application in terms of dose, time, and application methodology, to alternative sources of N that reduce losses and increase use efficiency. The modeling tools contribute to a better diagnosis of the behavior of the nutrients added with fertilizer and the reduction of the risks of contamination and eutrophication.

Sensor technology represents a useful strategy in soil monitoring with the advantage of obtaining information at a high spatial density, but without externalities such as chemical waste production. The concept of soil sensing was coined in 2011 and implies the use of soil sensors directly on the field. Proximal soil sensing technique is a multidisciplinary approach that involves instrumentation, data science, geostatistics, and predictive modeling. The integration of these disciplines has allowed successful sensor application for the spatial diagnosis of soil fertility attributes. Advances in sensors compatible with on-line measurement systems and portable sensor systems complement each other well and have proven to be useful. An example are measurement methodologies such as mobile laboratories (Pandey *et al.*, 2017).

Spectroscopy is the study of the interaction between matter and electromagnetic radiation. Visible and near-infrared spectroscopy (Vis-NIRS) and mid-infrared spectroscopy (MIRS) have been successfully used *in situ* and on-line measurement platforms for determining total soil N. Modeling and management of spectral data are important steps for the development of these techniques, such as the variable rate N fertilization. This refers to the application of the right rate of N fertilizer in the right place at the right time using advanced precision agriculture technologies (Guerrero Castillo, De Neve and Mouazen, 2021). The adoption of Vis-NIRS and MIRS techniques has increased their cost-effectiveness and accuracy not only in the case of soil N, but also for the determination of different aspects of soil analysis directly affecting soil fertility. Some soil properties that can be estimated using Vis-NIRS and MIRS are particle sizes, aggregation, surface roughness and water content (FAO, 2022). The Global Soil Partnership through the Global Soil Laboratory Network (GLOSOLAN) launched the soil spectroscopy initiative (GLOSOLAN-Spec) in 2020, which focused on national capacity development and the creation and development of national and regional soil spectral libraries. These libraries allow different countries to access a wide range of soil, and over the long term, national and regional soil maps can be improved and used to enhance the implementation of SSM practices.

The use of optical sensors has been shown to be a useful tool to increase the NUE and apply the appropriate dose of N and P fertilizer in different regions of the world (Ortíz-Monasterio and Raun, 2007; Lapidus *et al.*, 2017). This technology is based on the use of a variation of the Normalized Vegetation Index (NDVI) and a linear relationship with crop N content to determine the required fertilizer dose (Crain, Ortiz-Monasterio and White, 2012). This technology allows to accurately predict the amount of N and P needed by a crop at a specific site which allows to achieve the maximum expected yield (Crain, Ortiz-Monasterio and White, 2012). Drawbacks of this type of strategies are the costs. The sensor costs vary depending on the level of technification, automation and synchronization with crop mechanization. However, technological advances have made possible the development of a smaller, cheaper, and portable but efficient version (Ortiz-Monasterio, 2017) that has increased the profits of farmers and has significantly reduced GHG emissions, specially N_2O (Lapidus *et al.*, 2017). Even so, the adoption of this technology in peasant agricultural production would be complex due to costs, training, technical support, and the lack of studies on the performance of these sensors in hillside agriculture. However, in the case of technified agriculture, it has been shown to generate savings for producers and reduce the addition of N without affecting yields.

Enhanced-efficiency fertilizers (EEF) have the potential to reduce N_2O emissions and improve crop productivity. Their efficiency depends on site characteristics and type of crop. In a meta-analysis covering 43 studies in different continents, Thapa *et al.,* (2016) found that nitrification inhibitors, double inhibitors (urease plus nitrification inhibitors) and controlled-release N fertilizers consistently reduced N_2O emissions compared with conventional N fertilizers across soil and management condition (grand mean decreases of 38, 30, and 19 percent, respectively).

Nutrient models are often developed integrated with crop growth simulation models, which require robust ecophysiological functionality to support reliable simulation of diverse genotype, management and environment combinations. Soufizadeh *et al.* (2018) tested and implemented a conceptual framework for functional modelling of maize crop N dynamics based on expressing crop N demand relative to canopy expansion, rather than on tissue N concentrations. A Windows program was developed to calculate the required seasonal N, P and K rates and the most cost-effective combination of commercial fertilizers (including estimates of the Ca, Mg and S balances in the field resulting from the fertilizer program chosen). It allows the users to determine the best complex fertilizer for pre-plant applications to avoid blending of simple fertilizers at the farm, a task usually complex for farmers (Villalobos *et al.*, 2020).

An important limitation for a more widespread adoption of crop and nutrient models is the need of available local robust information. In countries in sub-Saharan Africa recommendations and crop management fertilization decisions are often based on traditional field experimentation. There is a gross limitation of the use of models as agricultural decision-making tools, which could be attributed to factors such as low capacity development due to limited training opportunities, and the general lack of support from national governments for model development and application for policy formulation (MacCarthy *et al.*, 2018).

The use of alternatives to fertilizers such as biochar for the improvement of NUE has been evaluated, but data are still scarce in tropical soils. In these soils, biochar N fertilizers had an average maize yield that was 26 percent higher than that of urea and resulted in a NUE 12 percent higher than that observed for urea. Both effects on yield and NUE were attributed to lower N release rates of the biochar-amended fertilizers compared to that of the conventional soluble N sources (Puga *et al.*, 2020).

In the case of P, academia, in collaboration with farmers, has advanced in the understanding of P fate and transport in diverse environments. However, there is still much to be researched and implemented to produce innovations in products and/or application techniques with a wide potential for adoption and above all that are efficient in the acquisition of P by plants. Important advances have been reported under specific scenarios such as highly calcareous soils where liquid formulations of phosphates have been applied replacing dry granules, which drastically reduced precipitation as poorly soluble calcium phosphate minerals.

Biostimulants are alternatives to improve soil fertility and include humic and fulvic acids, amino acids and peptide mixtures. Other N molecules also considered biostimulants include betaines, polyamines and non-protein amino acids, which are very diverse in the plant world and their beneficial effects on crops are poorly characterized. Algae and plant extracts, chitosans, and other biopolymers are also used as biostimulants (Du Jardin, 2015). There are also inorganic compounds that are considered beneficial elements (e.g. Al, Co, Na, Se and Si) because they promote plant growth and may be essential for some but not all species. Some advantages of biostimulant application include the improvement of efficiency in the absorption and assimilation of nutrients, tolerance to biotic or abiotic stresses, or improving any of their agronomic characteristics. Biostimulants could complement and in some cases substitute chemical agro products; that could improve plants metabolism and biochemical activities. A wide variety of microbes can perform as plant biostimulants improving the efficiency of nutrition, several crop quality features, plant growth, and the tolerance to abiotic stress. However, biostimulants are relatively new products, so their regulation is not yet completely clear and non-existent in some cases, which may lead to the marketing of low-quality products. Therefore, regulation and quality assessment is needed. More research is needed to understand the mechanisms and functioning in crops and soils. In addition, price is a factor that could hinder the experimental research and adoption of biostimulants can be more expensive than certain type of fertilizers.

The combination of the use of beneficial and environmentally friendly microorganisms for agricultural production such as P solubilizers and N fixers together with inorganic fertilizers is an increasingly important line of research aimed at developing microbial formulations that enhance the benefits of mineral inputs reducing negative effects on the environment. Since most agricultural systems are N- and P-limited, this novel approach is likely to be of global interest. Evidence shows that even a single polymicrobial inoculation (Figure 14) can have positive effects on agricultural productivity (Bargaz *et al.*, 2018).

The microbial consortia concept

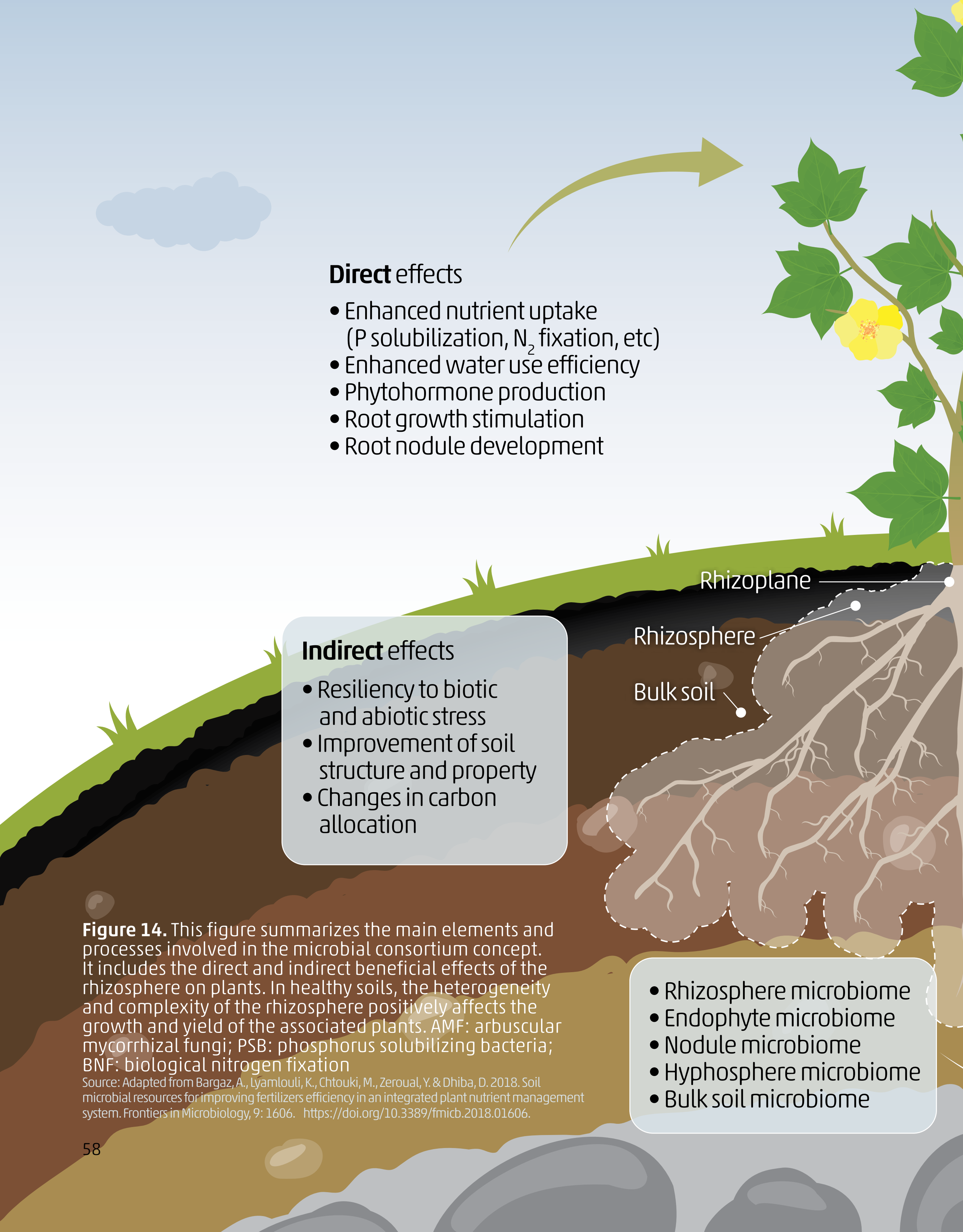
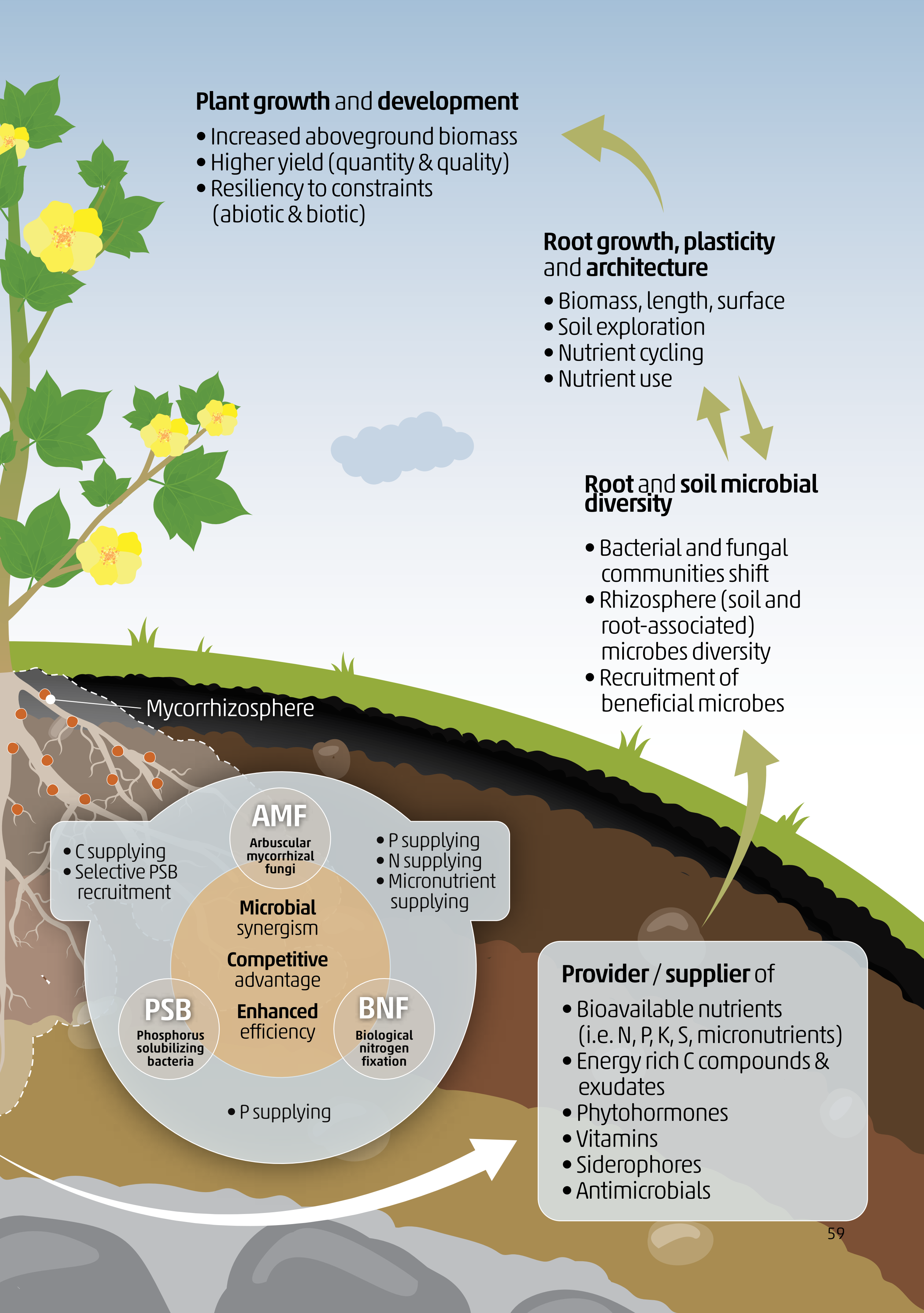


Figure 14. This figure summarizes the main elements and processes involved in the microbial consortium concept. It includes the direct and indirect beneficial effects of the rhizosphere on plants. In healthy soils, the heterogeneity and complexity of the rhizosphere positively affects the growth and yield of the associated plants. AMF: arbuscular mycorrhizal fungi; PSB: phosphorus solubilizing bacteria; BNF: biological nitrogen fixation

Source: Adapted from Bargaz, A., Lyamlouli, K., Chtouki, M., Zeroual, Y. & Dhiba, D. 2018. Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. Frontiers in Microbiology, 9: 1606. https://doi.org/10.3389/fmicb.2018.01606.



Plant growth and development
• Increased aboveground biomass
• Higher yield (quantity & quality)
• Resiliency to constraints (abiotic & biotic)
Root growth, plasticity and architecture
• Biomass, length, surface
• Soil exploration
• Nutrient cycling
• Nutrient use
Root and soil microbial diversity
• Bacterial and fungal communities shift
• Rhizosphere (soil and root-associated) microbes diversity
• Recruitment of beneficial microbes
Mycorrhizosphere
AMF
Arbuscular mycorrhizal fungi
• C supplying
• Selective PSB recruitment
• P supplying
• N supplying
• Micronutrient supplying
Microbial synergism
Competitive advantage
Enhanced efficiency
PSB
Phosphorus solubilizing bacteria
BNF
Biological nitrogen fixation
• P supplying
Provider / supplier of
• Bioavailable nutrients (i.e. N, P, K, S, micronutrients)
• Energy rich C compounds & exudates
• Phytohormones
• Vitamins
• Siderophores
• Antimicrobials

3.6. The role of reused and recycled nutrient sources.

According to the Fertilizer Code, recycled nutrients are plant nutrients applied to and taken up by growing plants that can be returned to the nutrient cycle after consumption by humans or animals, as by-products of food processing, or as plant residues returned to the soil (FAO, 2019c). The reuse of nutrients and recycled materials that come from various sources including wastewater, algae biomass, aquatic plants, sewage sludge, biosolids, animal manure, urban wastes, composts, vermicompost, digestates, biochar, inorganic or organic byproducts such as struvite, ammonium sulfate and residues from food, agroindustry, and other industries aims at closing fertilizer products life cycles and achieving circular economy objectives (Figure 15). Plant growth and yield potentials with recovered nutrients can be either similar or better than that of the conventional fertilizer. To ensure eco-friendly application of the recovered nutrient, the presence of undesirable contaminant fractions (e.g. heavy metals) should be eliminated (Saliu and Oladoja, 2021).

The reuse of edible food material is the most socially responsible utilization approach. Because of this, actions against the wastage of food consequently have an impact on the feedstock availability of utilization processes. It is assumed that due to economic reasons more edible food fractions are processed for instance in biorefineries to produce high value products. The inedible fraction of wasted food material can find its way in recycling processes where it is most efficiently converted into new products (Pleissner, 2018).

The transition to the circular nutrient economy calls for policy measures that encourage the production and use of composts and digestates, as well as the necessary logistics to enable their use. These policies should avoid inefficient nutrient use; generate demand for recycled fertilizers; and provide support for biomass processing before the markets for recovered resources are up and running. Public and private investments, technological developments and institutional shifts can create conditions for profitable and safe production and consumption of recycled nutrients (Valve, Ekholm and Luostarinen, 2020).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Recycling nutrients for circular economy and zero wastes

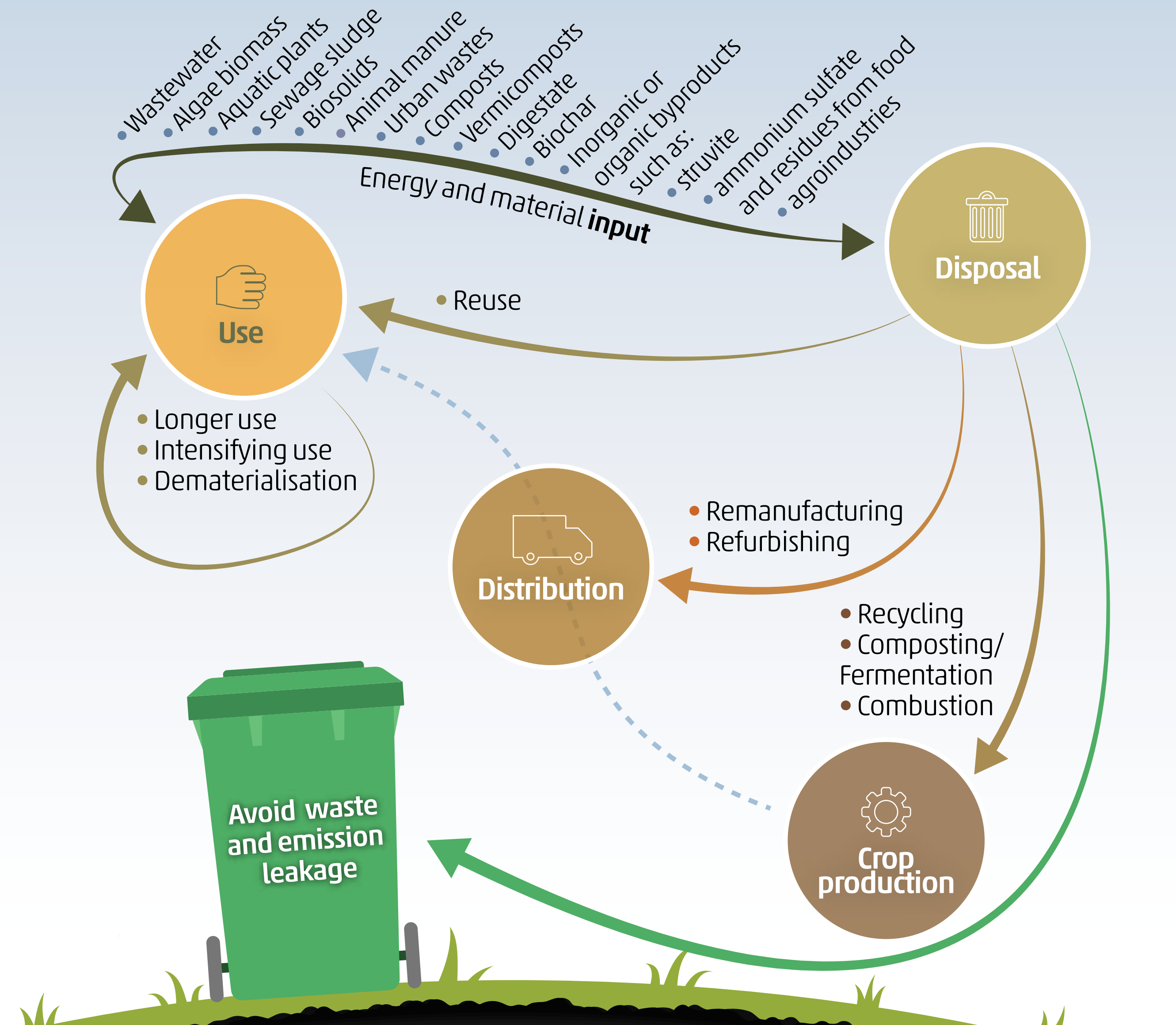


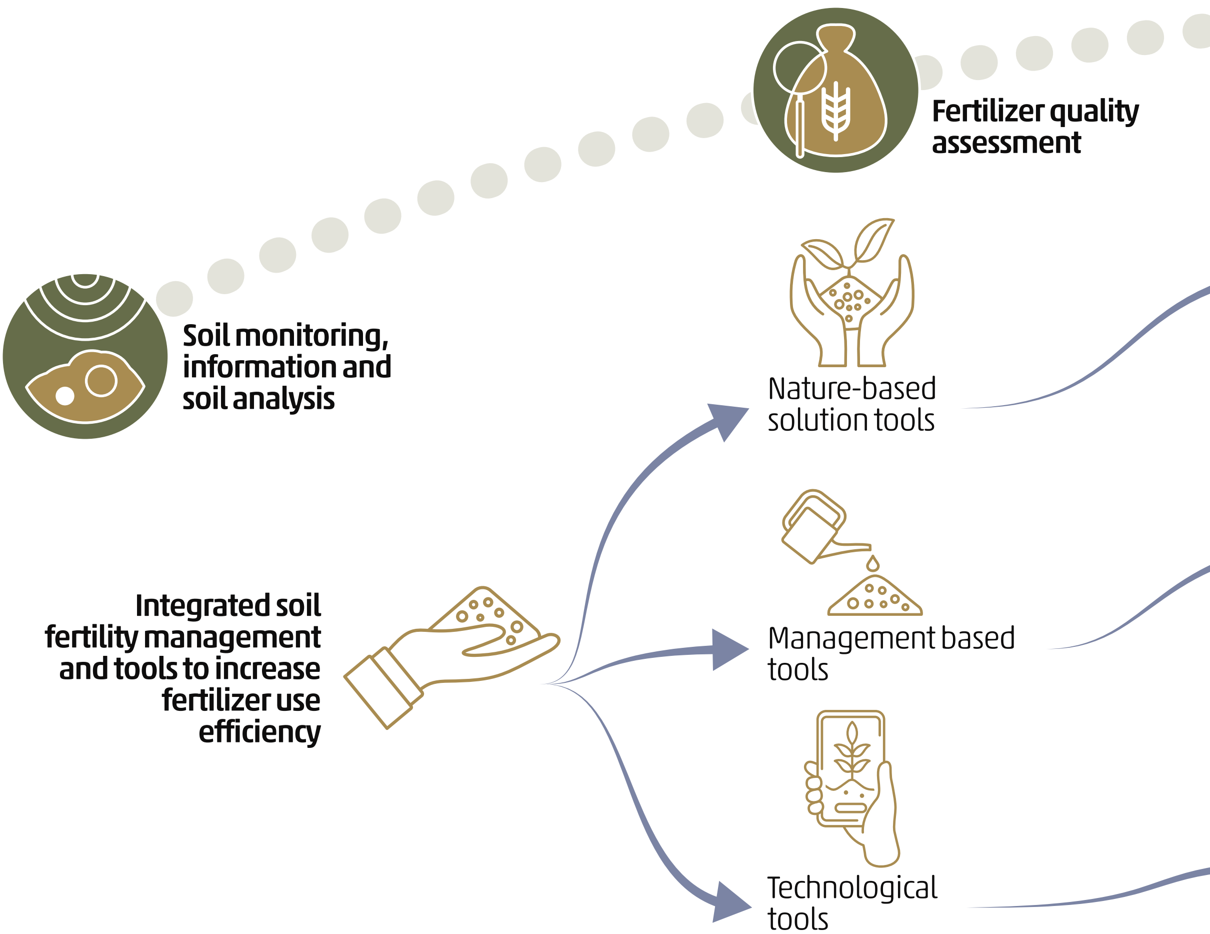
Figure 15. Several nutrient sources, wastes, and byproducts of fertilizers could be processed under a circular economy framework and be used again to improve soil fertility

Source: Adapted from Geissdoerfer, M., Pieroni, M.P., Pigosso, D.C. & Soufani, K. 2020. Circular business models: A review. Journal of Cleaner Production, 277: 123741. https://doi.org/10.1016/j.jclepro.2020.123741.

3.7. Sustainable soil fertility management

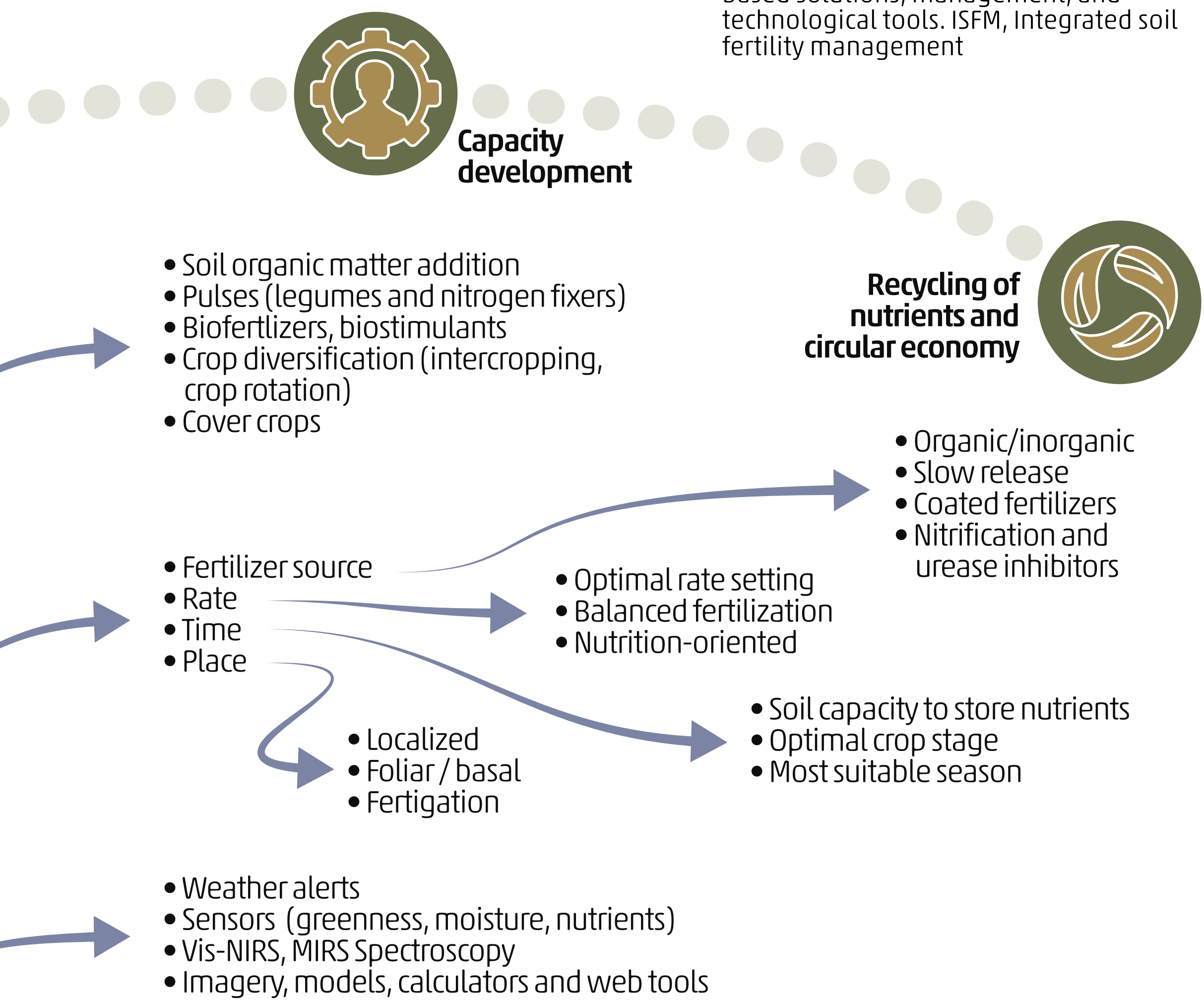
Nutrients present in soils and added through fertilizers function as nutrients when they are within the plant-soil-atmosphere system. However, under a scheme of fertilizer overuse or misuse, nutrients are prone to leaking out of the system, behaving as triggering agents of environmental pollution, climate change and damage to human health. In this sense, it is more cost-effective to direct efforts towards preventive, more than corrective approaches. However, the matter of what to do and how to retrieve leaked nutrients from the atmosphere and water bodies back to the soils require also research and investment.

Fertilizer use recommendations based on an integral approach



Since most fertilizers come from the extraction of minerals, which are non-renewable natural resources with an uncertain life span, it is necessary to optimize the use of fertilizers. Amid environmental problems and climate change, it is necessary to develop and strengthen alternatives that complement or replace the use of mineral fertilizers. Underuse, overuse and misuse of fertilizers is a multifactorial problem, and proper recommendations to optimize fertilizer use can contribute significantly to avoid the externalities associated with inappropriate fertilizer use. There is currently a wide array of strategies and tools to support fertilization plans including NbS, management-based strategies and technological tools which have been included in this review. The cost effectiveness and adoption of these strategies can greatly benefit from essential pillars for SSM including soil monitoring, soil information, soil analysis, capacity development, fertilizer quality assessment and the inclusion of circular economy approaches (Figure 16).

Figure 16. Integral approach for fertilizer uses recommendation based on nature-based solutions, management, and technological tools. ISFM, Integrated soil fertility management



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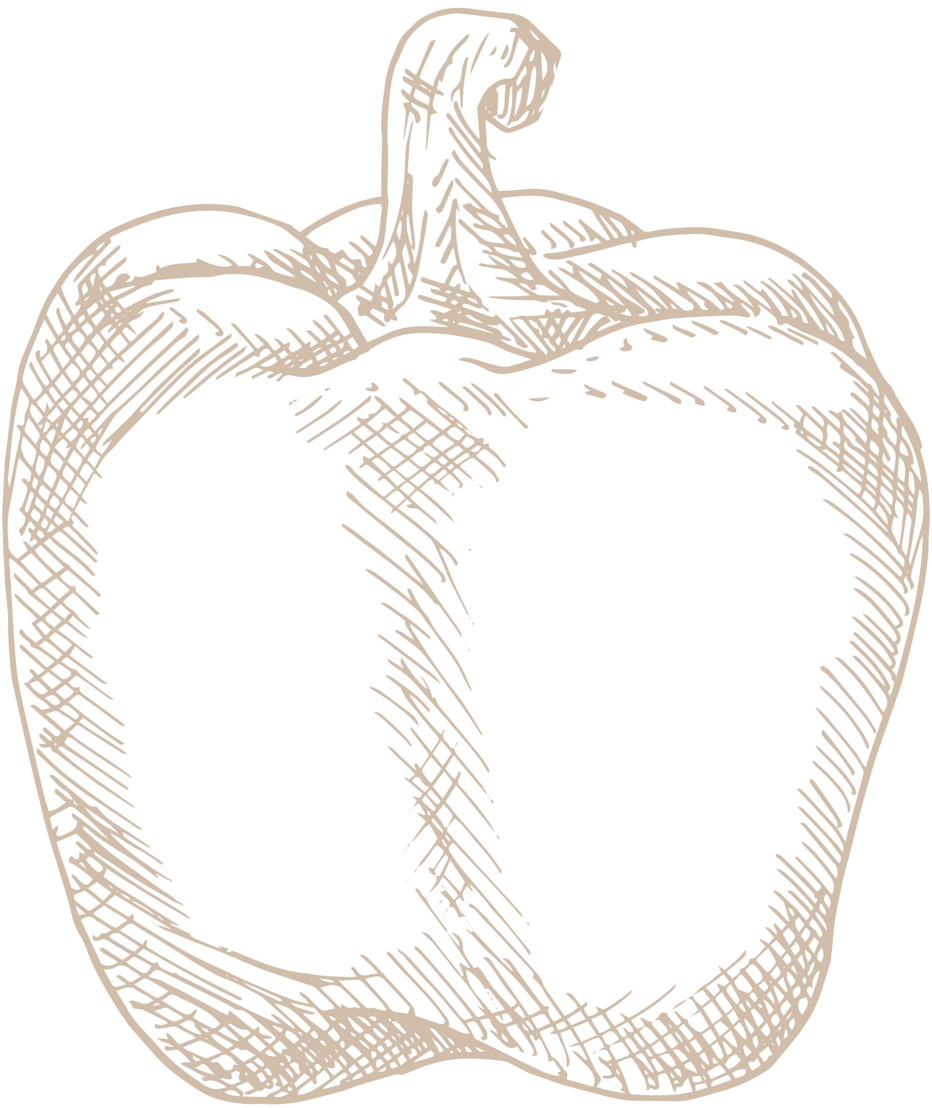

Glossary

Adsorption: The attraction of ions or compounds to the surface of a solid. Soil colloids adsorb large amounts of ions and water (Weil and Brady, 2017).

Ammonia volatilization: The loss of nitrogen to the atmosphere in the form of ammonia after applications of fertilizers (FAO,2019c).

Bioavailability: The measure of fractional utilization of orally ingested nutrient and also defined as the proportion of a particular nutrient that can be used by the body to provide its associated biological function. The amount of an element in a food constituent or a meal that can be absorbed and used by a person. Bioavailability also refers to the portion of an ingested nutrient that can be absorbed in the human gut. The bioavailability of minerals can be reduced or enhanced by the consumption of food rich in antinutrients (inhibitors of absorption) or nutritional enhancers, respectively (Singh *et al.*, 2016).

Biofertilizer: A broad term used for products containing living or dormant micro-organisms such as bacteria, fungi, actinomycetes and algae, alone or in combination, which on application help in fixing atmospheric nitrogen or solubilize/ mobilize soil nutrients (FAO,2019c).

Biogenic nitrogen: Biogenic emissions of N_2O from soils result primarily from the microbial processes nitrification and denitrification (Dolman, Valentini and Freibauer, 2008).

Biological invasion: When an organism arrives at a point beyond its previous range (Williamson and Griffiths, 1996).

Biological nitrogen fixation: The biological conversion of elemental nitrogen (N_2) to organic combinations or to forms readily utilized in biological processes. Occurs at ordinary temperatures and pressures. It is commonly carried out by certain bacteria, algae, and actinomycetes, which may or may not be associated with higher plants (Weil and Brady, 2017).

Black soils: Soils with thick, dark-coloured horizons, that are rich in organic carbon (FAO,2022).

Cation exchange capacity: The total of exchangeable cations that a soil can adsorb. Sometimes called total-exchange capacity, base-exchange capacity, or cation-adsorption capacity. Expressed in centimoles of charge per kilogram (cmolc/ kg) of soil (or of other adsorbing material, such as clay) (Weil and Brady, 2017).

Chelation: The coordinate bonding of a metal with a molecule, usually of organic matter (Weathers, Strayer and Likens, 2013).

Circular economy: An economic system designed with the intention that maximum use is extracted from resources and minimum waste is generated for disposal (Deutz, 2020).

Colloid: Organic and inorganic matter with very small particle size and a correspondingly large surface area per unit of mass (Weil and Brady, 2017).

Controlled release fertilizers: Fertilizers that release nutrients in a controlled manner to satisfy the nutrient uptake of a crop (Rajan *et al.*, 2021).

Decomposition: Chemical breakdown of a compound (e.g. a mineral or organic compound) into simpler compounds, often accomplished with the aid of microorganisms (Weil and Brady, 2017).

Denitrification: The biochemical reduction of nitrate or nitrite to gaseous nitrogen, either as molecular nitrogen or as an oxide of nitrogen (Weil and Brady, 2017).

Desorption: The removal of sorbed material from surfaces (Weil and Brady, 2017).

Dissolution: Process by which molecules of a gas, solid, or another liquid dissolve in a liquid, thereby becoming completely and uniformly dispersed throughout the liquid's volume (Weil and Brady, 2017).

Enhanced efficiency fertilizers: Fertilizers that reduce loss to the environment and/or increase nutrient availability compared to conventional fertilizers (Olson-Rutz, Jones and Dinkins, 2011).

Erosion: The wearing away of the land surface by running water, wind, ice, or other geological agents, including such processes as gravitational creep. Detachment and movement of soil or rock by water, wind, ice, or gravity (Weil and Brady, 2017).

Eutrophication: The excessive enrichment of surface waters with plant nutrients, primarily Nitrogen and Phosphorus (FAO,2019c).

Fertilizer: Any organic or inorganic material of natural or synthetic origin added to a soil to supply certain elements essential to the growth of plants (Weil and Brady, 2017).

Fertilizer use efficiency: An estimate or determination of the amount of nutrients in a fertilizer that are taken up by the crop after the fertilizer is applied to the soil as a proportion of the amount added. This can be for the crop grown after the initial fertilizer application is made or after one or more crops are grown (FAO,2019c).

Fixation: For other than elemental nitrogen: the process or processes in a soil by which certain chemical elements are converted from a soluble or exchangeable form to a much less soluble or to a nonexchangeable form; for example, potassium, ammonium, and phosphorus fixation. (2) For elemental nitrogen: process by which gaseous elemental nitrogen is chemically combined with hydrogen to form ammonia. (Weil and Brady, 2017).

Hypoxia: State of oxygen deficiency in an environment so low as to restrict biological respiration (in water, typically less than 2 to 3 mg O_2/L) (Weil and Brady, 2017).

Immobilization: The conversion of an element from the inorganic to the organic form in microbial tissues or in plant tissues, thus rendering the element not readily available to other organisms or to plants (Weil and Brady, 2017).

Labile: A substance that is readily transformed by microorganisms or is readily available for uptake by plants (Weil and Brady, 2017).

Leaching: The removal of materials in solution from the soil by percolating waters (Weil and Brady, 2017).

Life cycle: Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (ISO, 2006).

Micas: Primary aluminosilicate minerals in which two silica tetrahedral sheets alternate with one alumina/magnesia octahedral sheet with entrapped potassium atoms fitting between sheets. They separate readily into visible sheets or flakes (Weil and Brady, 2017).

Mineral apatite: A phosphate of calcium, with fluorine and chlorine [Ca_5(F, OH, Cl)$(PO_4)_3$]; the main source of phosphorus in the Earth´s crust (Deb and Sarkar, 2017).

Microbiome: The combined genetic material of all microorganisms living in a given ecosystem, including in the human body (FAO, 2019a).

Mineralization: The conversion of an element from an organic form to an inorganic state because of microbial decomposition (Weil and Brady, 2017).

Morbidity: The consequences and complications (other than death) that result from a disease (Morgan and Summer, 2008).

Mortality rate: The annual measurement of how many people die and the causes. Mortality data allow health authorities to evaluate how they prioritize public health programs. Deaths can be represented as a total number per year, or as a rate per 100 000 population per year. The numbers of deaths per 100 000 population are influenced by the age distribution of the population (WHO, 2022b).

Nitrification: The biochemical oxidation of ammonium to nitrate, predominantly by autotrophic bacteria (Weil and Brady, 2017).

Biological Nitrogen fixation: The biological conversion of elemental nitrogen (N_2) to organic combinations or to forms readily utilized in biological processes (Weil and Brady, 2017).

Nitrification inhibitor: A substance that inhibits biological oxidation of ammoniacal nitrogen to nitrate (FAO, 2019c).

Nutrient bioavailability: The fraction of a nutrient in a food that is absorbed and utilized (Wood, 2005).

Nutrition-sensitive agriculture: An approach that seeks to ensure the production of a variety of affordable, nutritious, culturally appropriate and safe foods in adequate quantity and quality to meet the dietary requirements of populations in a sustainable manner (FAO, 2017).

Organic fertilizer: By-product from the processing of animal or vegetable substances that contain sufficient plant nutrients to be of value as fertilizers (Weil and Brady, 2017).

Oxidation: The loss of electrons by a substance; therefore, a gain in positive valence charge and, in some cases, the chemical combination with oxygen gas (Weil and Brady, 2017).

Pedogenic processes: At the macro-scale there are five main principal pedogenic processes acting on soils: laterization, podzolization, calcification, salinization and gleization (Pidwirny, 2021).

Pool: A portion of a larger store of a substance defined by kinetic or theoretical properties. For example, the active pool of soil organic matter is defined by its rapid rate of microbial turnover (Weil and Brady, 2017).

Primary mineral: A mineral that has not been altered chemically since deposition and crystallization from molten lava (Weil and Brady, 2017).

Properties of soil colloids: The general properties of soil colloids are size, surface area, surface charges, adsorption of cations, adsorption of water, cohesion, adhesion, swelling and shrinkage, dispersion and flocculation, brownian movement, and non permeability (Channarayappa and Biradar, 2018).

Reactive nitrogen: All forms of nitrogen that are readily available to biota (mainly ammonia, ammonium, and nitrate with smaller quantities of other compounds including nitrogen oxide gases) as opposed to unreactive nitrogen that exists mostly as inert N_2 gas (Weil and Brady, 2017).

Reduction: The gain of electrons, and therefore the loss of positive valence charge, by a substance. In some cases, a loss of oxygen or a gain of hydrogen is also involved (Weil and Brady, 2017).

Runoff: The portion of the precipitation on an area that is discharged from the area through stream channels. That which is lost without entering the soil is called surface runoff and that which enters the soil before reaching the stream is called groundwater runoff or seepage flow from groundwater. (In soil science runoff usually refers to the water lost by Surface flow; in geology and hydraulics runoff usually includes both surface and subsurface flow (Weil and Brady, 2017).

Secondary mineral: A mineral resulting from the decomposition of a primary mineral or from the reprecipitation of the products of decomposition of a primary mineral (Weil and Brady, 2017).

Soil organic matter: The organic fraction of the soil that includes plant, animal and microbial residues in various stages of decomposition, biomass of soil microorganisms, and substances produced by plant roots and other soil organisms. It is commonly determined as the total organic (non-carbonate) carbon in a soil sample passed through a 2-mm sieve (Weil and Brady, 2017).

Soil solution: The aqueous liquid phase of the soil and its solutes, consisting of ions dissociated from the surfaces of the soil particles and of other soluble materials (Weil an Brady, 2017).

Value Chain: A chain of activities for a firm operating in a specific industry (Porter's, 1985).

Weathering: All physical and chemical changes produced in rocks, at or near the Earth's surface, by atmospheric agents (Weil and Brady, 2017).

GLOBAL SOIL PARTNERSHIP

The Global Soil Partnership (GSP) is a globally recognized mechanism established in 2012. Our mission is to position soils in the Global Agenda through collective action. Our key objectives are to promote Sustainable Soil Management (SSM) and improve soil governance to guarantee healthy and productive soils, and support the provision of essential ecosystem services towards food security and improved nutrition, climate change adaptation and mitigation, and sustainable development.

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Rome, Italy

SOILS: WHERE FOOD BEGINS

Thanks to the financial support of

Federal Ministry of Food and Agriculture

ISBN 978-92-5-136610-3
9 789251 366103
CC0900EN/1/07.22