Food and Agriculture Organization of the United Nations

Soils, where food begins

Outcome document of the Global Symposium on soils for nutrition

26-29 July 2022

GLOBAL SOIL PARTNERSHIP

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Content

Figures

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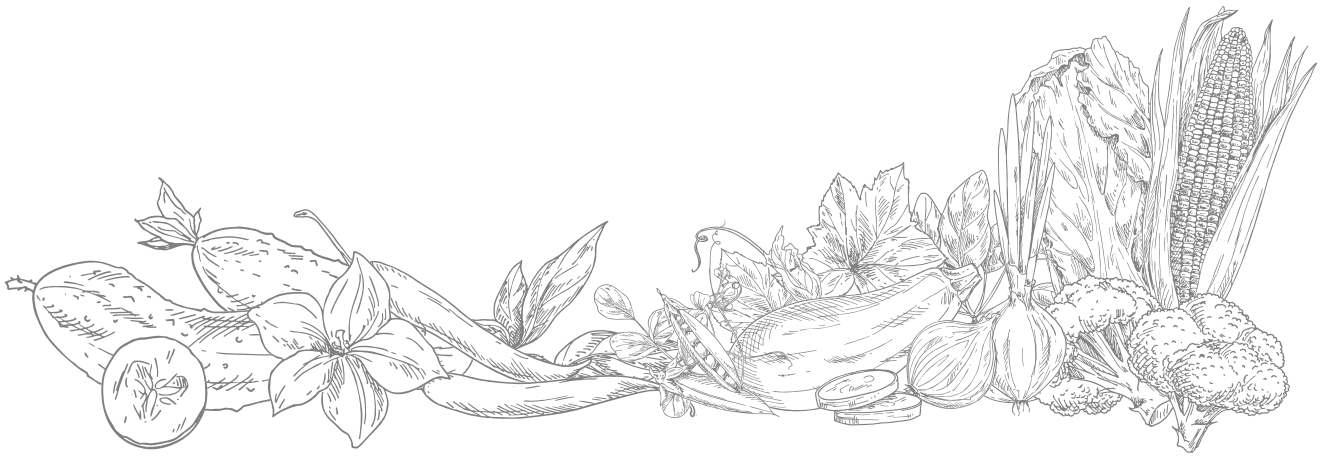

Scientific and organizing committees

This outcome document was prepared and reviewed by members of the Scientific and the Organizing Committees but does not necessarily represent the views of FAO Members. This document is also based on and complemented by the booklet Soils for Nutrition: State of the Art, and the proceedings, which presents extended abstracts of the various sessions.

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Chemical formulae and elements

CH_4	methane
CO_2	carbon dioxide
Fe	iron
K	potassium
N	nitrogen
N_2O	nitrous oxide
P	phosphorus
S	sulphur
Se	selenium
Zn	zinc

Abbreviations and acronyms

FAO	Food and Agriculture Organization of the United Nations
GHG	greenhouse gas
GSNmap	Global soil nutrient and nutrient budget map
GSOIL4N	Global symposium on soils for nutrition
GSP	Global Soil Partnership
ITPS	Intergovernmental Technical Panel on Soils
NSL	Land and water division, FAO
NUE	nutrient use efficiency
SDG´s	Sustainable Development Goals
INSOILFER	International Network of Soil Fertility and Fertilizers
SOM	soil organic matter
SSM	sustainable soil management
SWSR	Status of the World's Soil Resources
VGSSM	Voluntary Guidelines for Sustainable Soil Management
WHO	World Health Organization
WSD	World Soil Day

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Foreword

The unfortunate increases in global food insecurity and malnutrition have created overwhelming challenges for us all. However, as soils primarily form, store, transform and recycle the nutrients needed for humans to survive, sustainable soil management can help address these challenges. The **Status of the World's Soil Resources** (FAO, 2015) and the **Voluntary Guidelines for Sustainable Soil Management** (FAO, 2017) set a precedent by identifying the main threats to soil health and recommending solutions to restore soil health and combat food insecurity, soil pollution and climate change.

Soil nutrient imbalance was identified as one of the major global threats to soils, caused by underutilization, misutilization, and overutilization of nutrients. It also has negative effects on agriculture, the environment and human beings. Our society demands safe and more nutritious food, with fewer greenhouse gas emissions and a lessened environmental impact. While countries have committed to the 2030 Agenda for Sustainable Development, it also requires the transformation of our agrifood systems to become more efficient, inclusive, resilient and sustainable in the future. Healthy soils are our allies in making this transformation a reality.

In this context, FAO's Global Soil Partnership (GSP) organized the **Global Symposium on Soils for Nutrition** between 26 and 29 July 2022. It provided a platform for presenting an array of scientific and technical knowledge, management practices, field trials, and multi-sectoral perspectives from stakeholders involved in soil fertility, nutrient imbalance, environmental pollution and climate change. The symposium collated the latest scientific findings, practical solutions and recommendations from more than 180 countries for addressing the global soil nutrient challenges. These will direct future actions in implementing the **International Code of Conduct for the Sustainable Use and Management of Fertilizers** (FAO, 2019).

The Outcome Document of the **Global Symposium on Soils for Nutrition: Soils, where food begins** reports an important step in positioning sustainable soil management as a direct contributor to improve crop, animal, and human health and nutrition, while reducing or avoiding pollution and greenhouse gas emissions.

The symposium was an important step, providing many collaborative actions to tackle soil nutrient imbalance. We call on all relevant stakeholders and countries to disseminate the findings and implement the recommendations in this Outcome Document to foster healthy soils for healthy crops, healthy people and a healthy planet.

Dr Lifeng Li

Director, Land and Water Division
Food and Agriculture Organization
of the United Nations

Executive summary

The Global Symposium on soils for nutrition (GSOIL4N) was organized by the Food and Agriculture Organization of the United Nations (FAO), its Global Soil Partnership (GSP) and its Intergovernmental Technical Panel on Soils (ITPS).

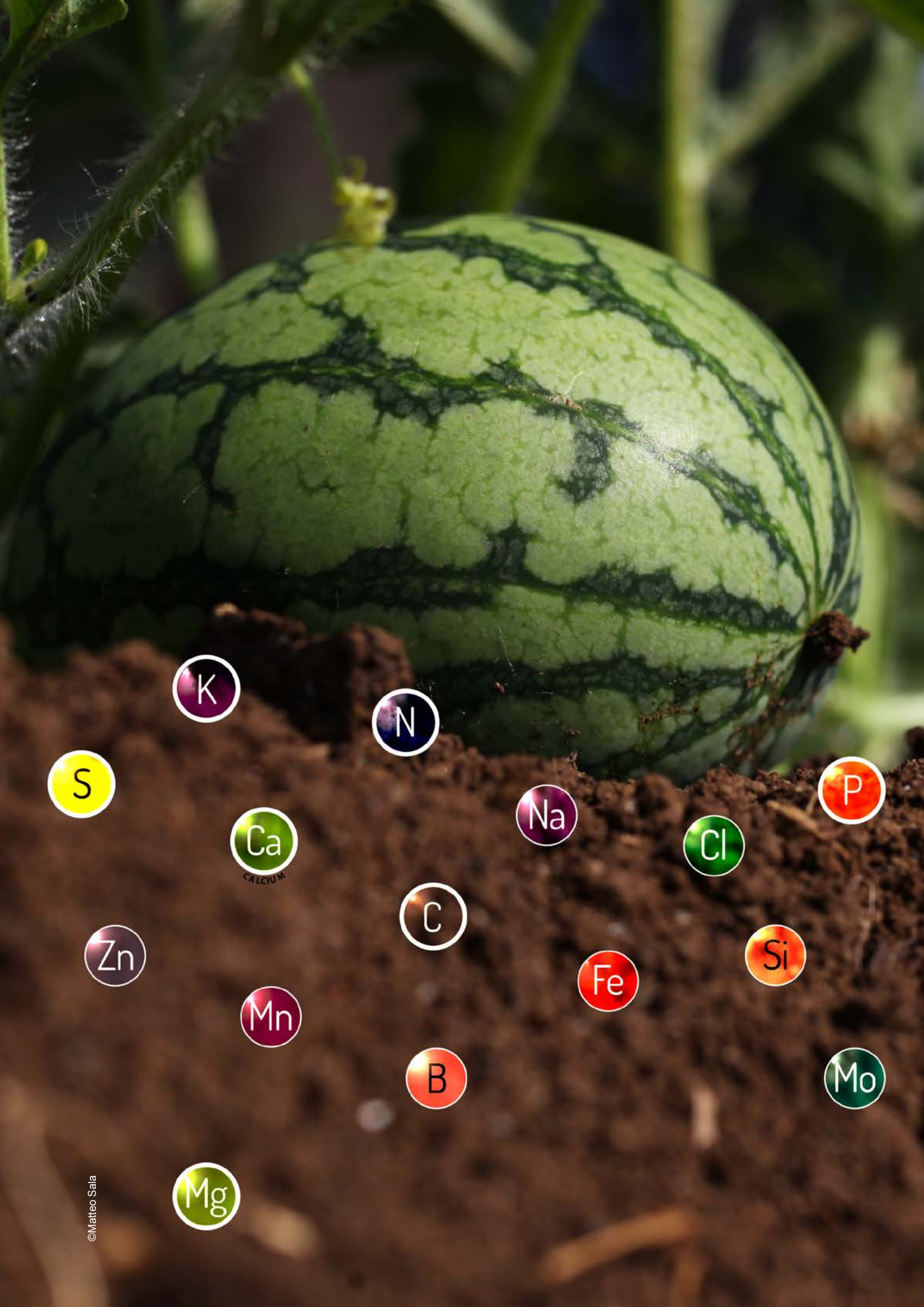
The symposium was held on 26 to 29 July 2022 in virtual mode. Over 9 500 participants (45 percent women, 55 percent men) registered for the symposium and more than 5 000 participants connected from 180 countries. The participants included representatives of FAO Members, organizing institutions, academia, the private sector and civil society, as well as scientists and land users working on soil fertility and related fields. During the symposium, there were over 80 presentations, eight hours of plenary sessions, 20 hours of presentations and discussions, 69 scientific posters that were voted in an online contest gaining almost 120 000 unique votes in four days. A photo contest on soils for nutrition was presented. In addition, 28 renowned speakers focused on how policy and scientific evidence can be translated into concrete actions to reduce soil fertility loss, moving towards nutrition and food security and the achievement of the Sustainable Development Goals (SDGs).

The symposium aimed at reviewing the state of the art on the role of soil fertility in delivering sufficient, high quality, safe, and more nutritious food for better-nourished plants, animals, and people and identifying the critical knowledge gaps. The information provided during the symposium promoted discussion among key stakeholders on the creation of solutions for producing more nutritious food, enhancing soils, plants, animals and human health according to the "One Health" approach, while protecting the environment. The One Health initiative is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems. It recognizes the health of humans, domestic and wild animals, plants, and the environment are closely linked and inter-dependent (OHHLEP, 2021).The four-day symposium was structured around four main themes focusing on: 1) status and trends of the global soil nutrient budget; 2) sustainable soil management for food security and better nutrition; 3) impacts of soil nutrient management on the environment and climate change; and 4) governance of soil fertility and soil nutrients.

Participants from around the world attended plenary panels in which experts from different sectors and perspectives exchanged views. The latest research and findings on the four symposium themes were summarized through presentations in parallel sessions and posters. In different fora, it was evidenced that **nutrient imbalance is a global and crosscutting threat** with multifactorial drivers and effects on the agrifood systems and even on key planetary processes. After the valuable insights from speakers and presenters, the **need for strengthening the mapping and monitoring of soil nutrients and soil fertility** was evidenced. It was also clear that actions needed to be taken to **increase organic and inorganic fertilizer use efficiency, avoid environmental pollution and greenhouse gas (GHG) emissions** through good soil management strategies, nature-based solutions, technological tools, and innovations. The need to **support alternative nutrient source innovation and recycling** was emphasized, along with the **monitoring of quality of all nutrient sources** to avoid human health problems and environmental degradation.

Through the speeches of policymakers, keynote speakers, expert panels, and the oral presentations and posters, the problems and solutions of the four themes were presented. At the end of the GSOIL4N, knowledge gaps on how soil fertility supports better production, better nutrition, a better environment, and a better life were identified.

The latest research findings and discussions were translated into key messages and recommendations for sustainably enhancing soil fertility. The recommendations presented in this document aim to support the implementation of actions and development of policies towards healthy and fertile soils by 2030, allowing the sustainable production of more nutritious and safer food with a climatic and environmentally friendly approach.



Background of the global symposium on soils for nutrition

Soils are a valuable natural resource of the planet (FAO and ITPS, 2015) that perform functions on which processes that enable the continuity of life on Earth depend. While soils are related to the provision of various ecosystem services (Lehmann *et al.*, 2020), one of the vital functions is food production. Soils are the basis for producing more than 95 percent of our food, since a wide variety of grains and vegetables rely on soils for their production, and livestock meat and dairy products are supported by animal feeds that also grow in soils (FAO and ITPS, 2023). The capacity of soils to support agrifood systems relies on soil fertility, a property that makes possible the transformation and availability of nutrients for plant uptake (Weil and Brady, 2017). Soil fertility is the result of the dynamic interaction of physical, chemical, and biological properties, on which the supply of nutrients and the support for plant growth are based. But soil fertility is rapidly being reduced or lost. According to the Status of the World's Soil Resources Report (SWSR) (FAO, 2015), about one-third of the world's soils show high or very high degradation due to several causes that are threatening soils functions. Erosion, soil organic carbon loss, nutrient imbalances, soil biodiversity loss, soil sodicity and salinity, among others are the main causes for soil degradation.

One of the main drivers of soil fertility loss is nutrient imbalance (FAO, 2022a), implying either the underuse, the misuse, or the overuse of nutrients. These contrasting and inappropriate usages of nutrients directly affect the production, quality, and safety of food. The lack of soil nutrients and failure to replenish soil organic matter (SOM) after harvest lead to nutrient-depleted soils, crop nutrient deficiencies, low crop yields or crop failure, less nutritious food, human and animal nutrient deficiencies, and ultimately impacts food security (FAO, 2022a). Excess nutrients in agricultural soils leads to serious problems in downstream water quality, including eutrophication, hypoxia and biodiversity loss in lakes, streams and coastal ecosystems, as well as biodiversity imbalances and species invasion in the oceans (Galloway *et al.*, 2003). However, the impacts of nutrients misuse and overuse are not limited to worsening water quality, as the effects generated by nutrient imbalances also contribute to the deterioration of land and atmospheric quality and aggravate global climate change (FAO, 2022a).

Due to the complex global scenario in which agricultural soil management is embedded, it is important to consider poverty, migrations and displacements, war conflicts, environmental deterioration, climate change, pandemics and the rise in fertilizer prices as co-occurring factors that also determine public welfare, exposing a vulnerable population to hunger, impoverishment, and lack of resilience to climate change. Amidst this intricate global environmental, economic, and social scenario, scientific knowledge and innovation stand as fundamental pillars that can lead to the conservation of soil fertility in a more efficient and more affordable way, releasing the multiple benefits associated with healthy soils.

Healthy soils deliver ecosystem services that enable life on Earth, including the provision of food, fibre, and fuel, carbon sequestration, water purification and soil pollution reduction, climate regulation, nutrient cycling, habitat for organisms, a source of pharmaceuticals and genetic resources, and flood regulation, among others (Brevik *et al.*, 2017).

The Global Symposium on soils for nutrition (GSOIL4N) emerges as an inclusive pathway that caters to the different voices of stakeholders involved in soil fertility and nutrient imbalance. The GSOIL4N arises from the need to know what the status of soil fertility in the world is, what are the factors that regulate its reduction or loss, and how they can be reversed to achieve food security and safety (Figure 1).

The International Code of Conduct for the Sustainable Use and Management of Fertilizers (The Fertilizer Code) (FAO, 2019) is an instrument to provide a locally adaptable framework and a voluntary set of practices to support the different stakeholders directly or indirectly involved with fertilizers. The Fertilizer Code was endorsed by the 41st Session of the FAO Conference in June 2019 and represents an important tool for implementing the Voluntary Guidelines for Sustainable Soil Management (VGSSM) (FAO, 2017), with special focus on nutrient imbalances and soil pollution. During the Eighth Plenary Assembly of the Global Soil Partnership (GSP), held on June 2020, a basic framework to support a strategic global implementation of the Fertilizer Code was formulated. One of the principal outcomes from this session was the mandate to "...disseminate the Fertilizer Code at the global level and raise awareness on the issues and principles mentioned in the Code". The GSOIL4N includes the principles of the Fertilizer Code, and is therefore a vehicle for its implementation. During the symposium, the major issues addressed by the Fertilizer Code were discussed: that is the underuse, misuse, and overuse of nutrients in agricultural soils, the causes, the strategies to combat them, and the way forward (Figure 1). Of relevance is the future establishment of the International Network on Soil Fertility and Fertilizers (INSOILFER) under the umbrella of the GSP. This new global network will allow an articulated response to the challenges of soil fertility and fertilizers in the different regions of the world.

The world is facing high soil degradation rates leading to soil fertility loss and the reduced capacity to support crop production, therefore it is urgent to act, particularly to combat nutrient imbalance and its many harmful impacts on food security and the environment.

In order to achieve the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs), it is of upmost importance to address the world's soil health problems. The GSOIL4N addressed how healthy soils could contribute to the achievement of the SDG 2: zero hunger, and how to contribute to the fulfilment of SDG 3: good health and wellbeing, SDG 5: gender equality, SDG 6: clean water and sanitation, SDG 11: sustainable cities and communities, SDG12: responsible production and consumption, SDG 13: climate action, SDG 14: life below water, and SDG 15: life on land. The GSOIL4N is a successful example of how partnership and enhanced collaboration (SDG 17) among all stakeholders contribute to advance towards the achievement of the SDGs (Figure 1).

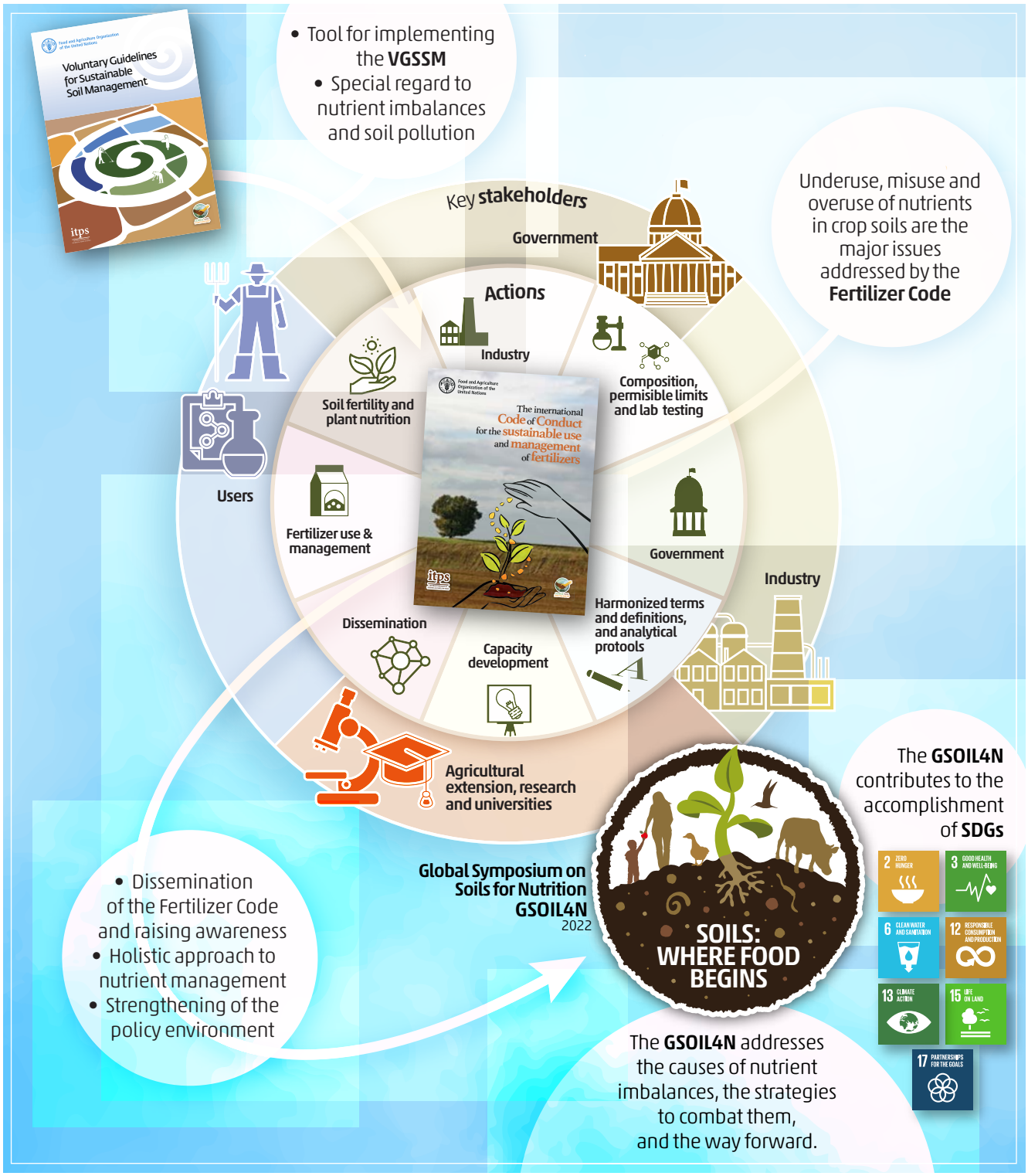


Figure 1. Background and origin of GSOIL4N and its alignment with the VGSSM, the Fertilizer Code, and the SDGs
Source: FAO/Global Soil Partnership

Positioning soils for nutrition in the public eye

A parallel goal of the GSOIL4N was to raise awareness on the importance of soils as a cornerstone for crop and human nutrition and health. To this end, a powerful communication campaign was launched during the GSOIL4N to reach a wide audience through:

- **Videos.** Two videos were developed in the framework of the symposium to contribute to knowledge dissemination about the close link between soils and the micronutrient content of food. The solutions to reverse the increasing trend of nutrient-depleted soil by adopting sustainable soil management (SSM) practices were also addressed in the videos. The videos were launched during the high-level opening session.
  - > The video **Healthy soils: the foundation of healthy food and a better environment** aimed to raise awareness on the risks associated with soil nutrient imbalance and soil fertility loss while highlighting the role of soil fertility in producing sufficient, safe, and more nourishing food for healthier plants, animals, and humans.
  - > The video **Bricks for life** was prepared by the Fossick Project for the GSOIL4N and it describes the story of a modern adventure in the nutrient cycle's world, from the soil below our feet to the table.
- **Social media cards**. A series of informative social media (SM) cards were developed to raise awareness on the role of soils on crop, human, and animal nutrition and the link between soil fertility and nutrient imbalances and deleterious environmental effects. Eleven cards were developed to raise awareness on the topics addressed in the GSOIL4N and to highlight issues related to World Soil Day (WSD) 2022 celebrations.
  - > Soils and nutrients
  - > Healthy soils grow 95 percent of our food
  - > Soil fertility is...
  - > Healthy soils and the nutrient cycle
  - > Healthy soils and their supply of chemical elements
  - > The challenge of nutrient balance
  - > Hidden hunger
  - > The Fertilizer Code
  - > Six actions to prevent and reverse nutrient imbalances
  - > Bring back nutrients to soils
  - > Six actions for farmers to fight nutrient imbalance
- **Booklet**. The booklet **Soils for nutrition: state of the art** was launched, during the Setting the Scene session on the first day of the symposium. The 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. It also outlines the main opportunity areas and the way forward to solve nutrient imbalances that are prevailing in our current agrifood systems.
- **Photo-contest** on #Soils4Nutrition. In the framework of the GSOIL4N, a photo contest was launched, aimed at soil scientists, environmentalists, activists, and soil fans. The intention was to illustrate the importance of soils for food security, nutritious food and healthy diets, nutrient deficiencies in crops, the danger of soil nutrient losses and nutritional imbalances, and management practices to improve soil fertility. Over 200 photos were received and they elicited a positive public reaction on social media with more than 1 000 likes and shares. During the symposium, the contest photos were voted on and the **winners** were announced on the last day of the symposium.
- **Presence in press**. The GSOIL4N was present in 96 dedicated articles in the international press, reaching 20 million people around the world.

Who attended the GSOIL4N?

Over 9 500 participants registered for the GSOIL4N, of which 45 percent were female, and 55 percent were male. During the eight hours of plenary sessions, nine distinguished guests and 21 renowned keynote speakers participated with an audience of more than 5 000 participants (on Zoom and webcast) on the first day, 3 500 participants on the second day, and 2 500 participants on the last day.

More than 300 scientific abstracts were submitted. During the 20 hours of parallel sessions and open discussion, 80 presentations were delivered, and 69 posters were available for virtual visiting and public voting over the three days. On the second day 2 137 participants attended the parallel session and 1 738 participants attended on the third day.

The majority of the participants came from Asia, Africa and Latin America and the Caribbean (Figure 2). The attendance of so many participants from different regions and in particular from developing countries was only made possible by the virtual format, and was not the case in the pre-2020 symposia.

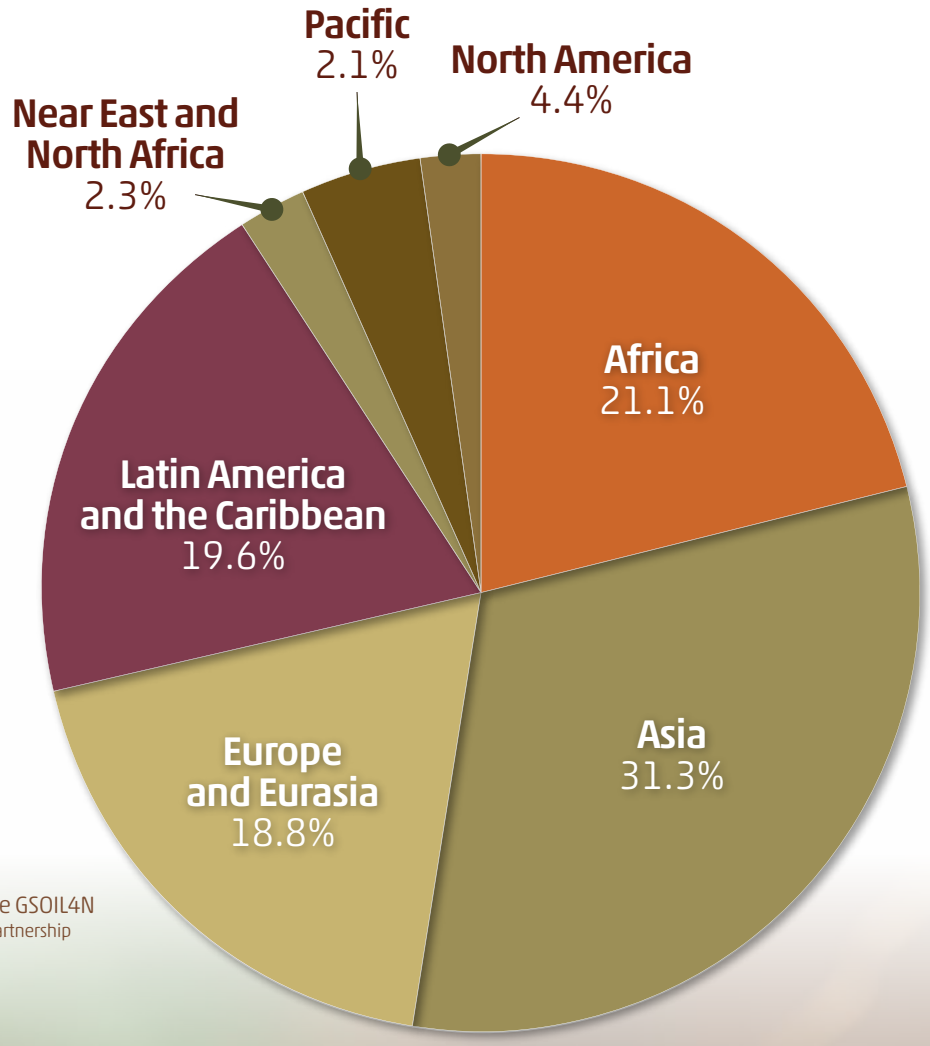


Figure 2. Regional representation at the GSOIL4N
Source: FAO/Global Soil Partnership

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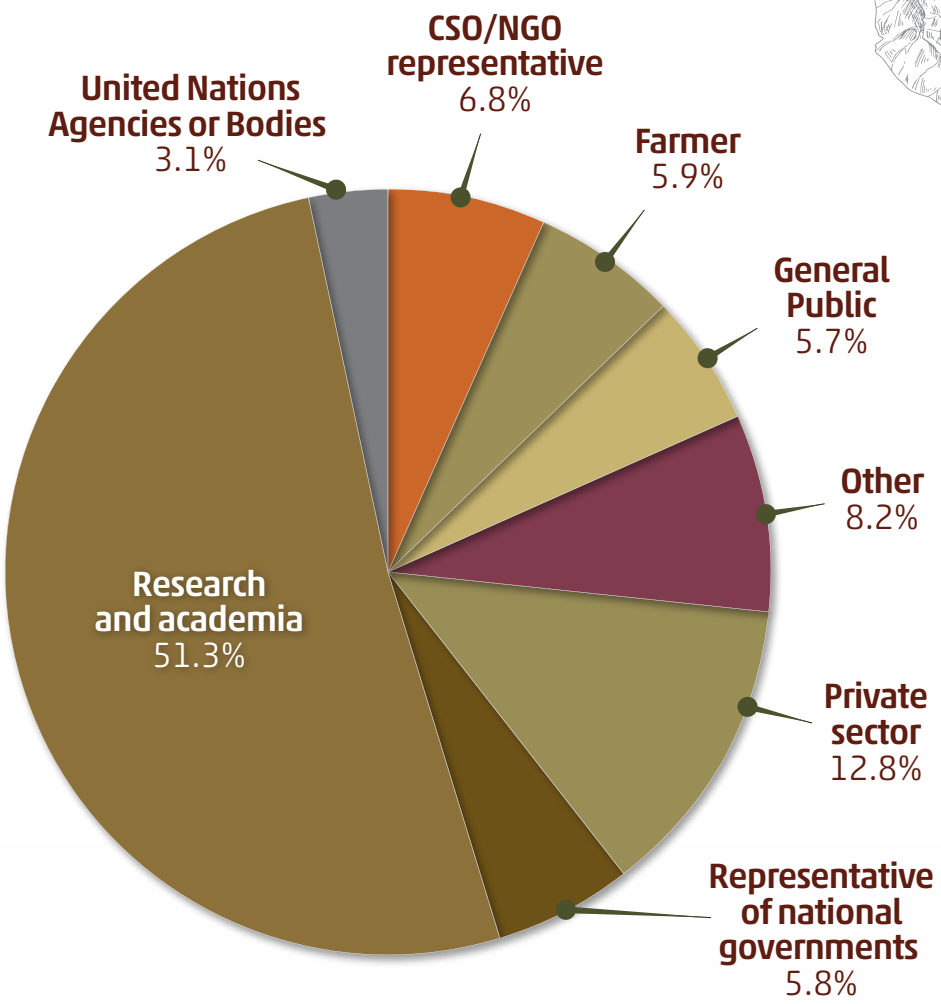
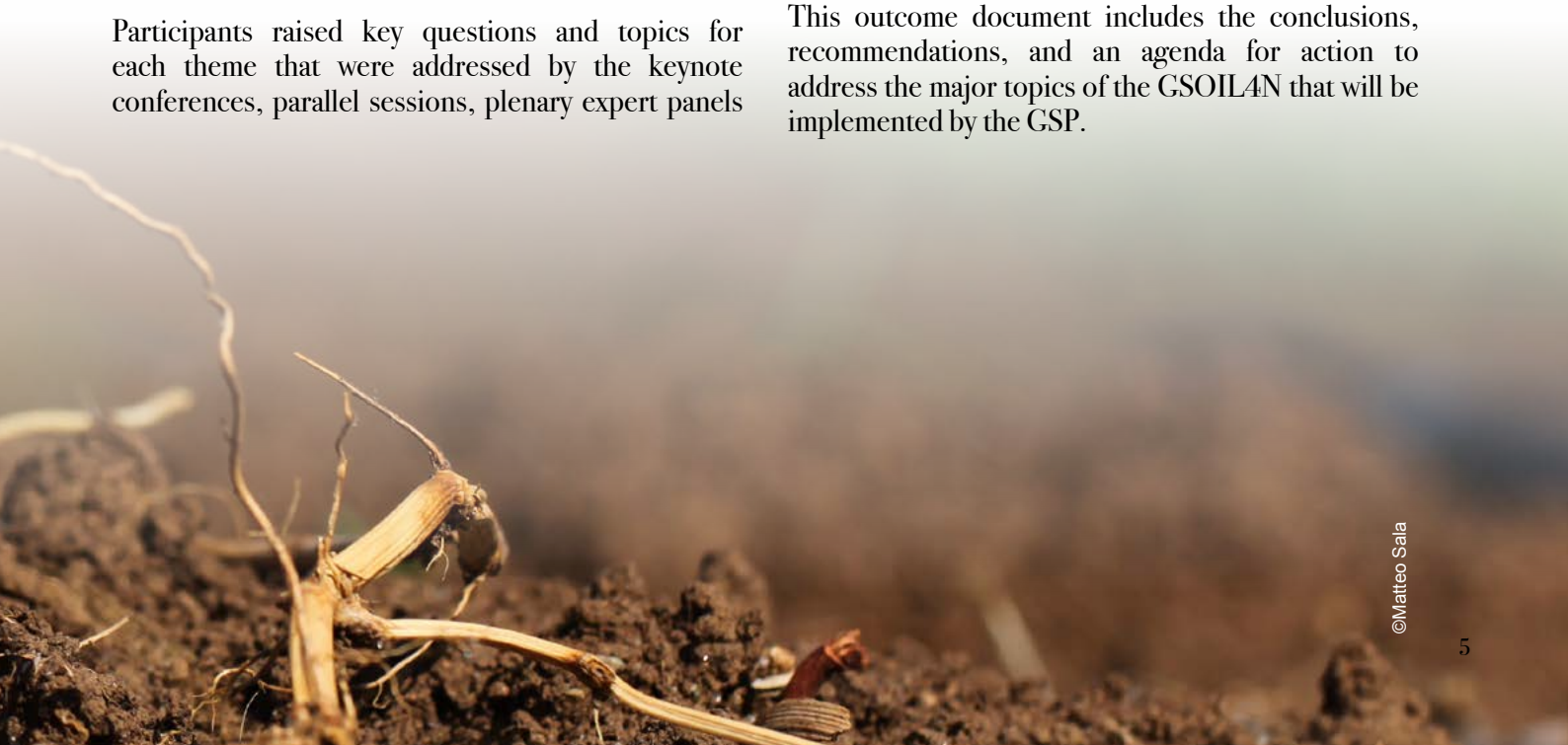


Figure 3. Participation of the different stakeholders in the GSOIL4N
Source: FAO/Global Soil Partnership

The GSOIL4N was a multistakeholder meeting, and although the research and academic sectors accounted for half of the participants, there were also representatives from the private sector, national governments, and the general public (Figure 3).

Participants raised key questions and topics for each theme that were addressed by the keynote conferences, parallel sessions, plenary expert panels and posters sessions. The open discussion contributed to identifying priority actions and recommendations to conserve and sustainably increase soil fertility. The GSOIL4N themes and sub-themes are listed in the following sections, with brief contextual summaries. This outcome document includes the conclusions, recommendations, and an agenda for action to address the major topics of the GSOIL4N that will be implemented by the GSP.



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Symposium objectives

The GSOIL4N aimed at reviewing the state of the art on the role of soil fertility in delivering sufficient, high quality, safe, and more nutritious food for better nourished plants, animals, and people. The symposium contributed to identify critical knowledge gaps and provide the basis for discussion among policymakers, food producers, scientists, the fertilizer industry, practitioners, and other stakeholders on the creation of solutions that could provide more nutritious agrifood systems for enhancing human health and well-being while protecting the environment.

Specifically, the symposium focused on:

- examining the current scientific, technical, and local knowledge on the role of integral soil fertility management for nutrition, food production, human health, and climate change mitigation opportunities;
- examining the knowledge on soil nutrient budgets, the application of external nutrients, and existing possibilities to match soil fertility to crop requirements;
- presenting innovative, effective, and replicable methodologies, technologies, and practices that promote sustainable crop and forage production, with a view on scaling these approaches to promote the sustainable management of soil fertility for crops and human nutrition;
- exploring different nutrient sources, their efficiency, and options for soil fertility management including analysis of their benefits and trade-offs related to fertilizers quality and potential environmental impact; and
- identifying policies that maintain and improve soil fertility and nutrition and encourage the adoption of effective practices that facilitate sustainable food production systems to meet food security.

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Symposium themes

Based on the global context affecting soil fertility and nutrient imbalances the symposium's four main themes (Figure 4) were designed to focus discussions on:

1. The status and trends of the global soil nutrient budget.
2. Sustainable soil management for food security and better nutrition.
3. The impacts of soil nutrient management on the environment and climate change.
4. The governance of soil fertility and soil nutrients.

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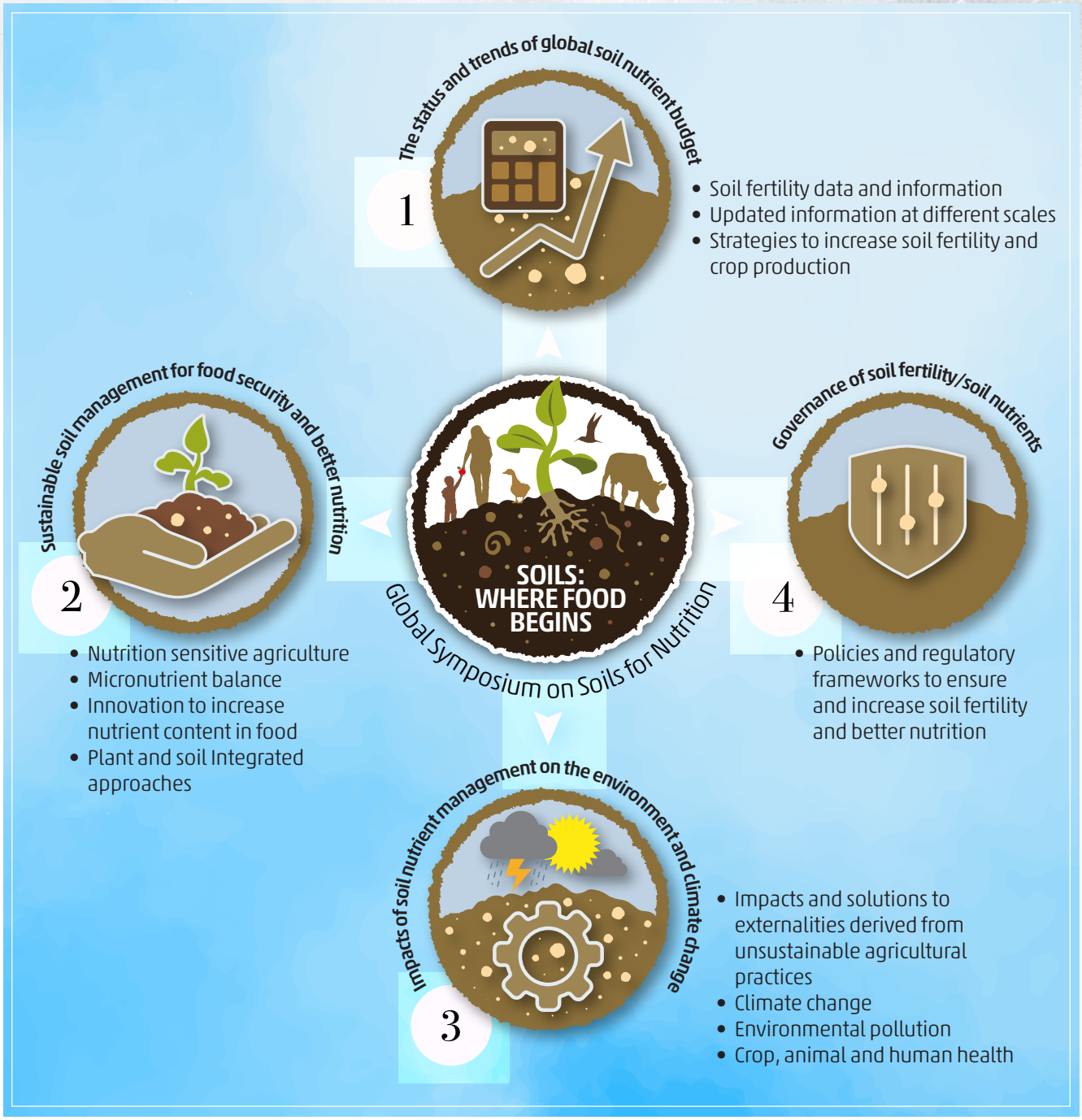

Figure 4. The four themes addressed in the GSOIL4N and the core topics covered within each theme
Source: FAO/Global Soil Partnership

Theme 1: status and trends of global soil nutrient budget and soil fertility

Within this theme, two sub-themes relevant to avoiding and reducing soil fertility loss were included: 1.1: Global soil nutrient budget, and 1.2: Strategies to increase soil fertility and crop production to support food security. Sub-theme 1.1 addressed the urgent need for updated, standardized, and accessible data and information on the soil nutrient budget, which implies accounting for the nutrients that enter and leave the soil. Sub-theme 1.2 addressed the strategies to sustainably increase soil fertility and crop production to support food security. The rapid deterioration of soils demands simultaneous actions for the sustainable increase of soil fertility and food production. In response to this need, strategies to improve physical, chemical, and biological fertility of agricultural soils were also addressed under this topic.

Sub-theme 1.1: global soil nutrient budget

Evidence-based soil fertility decision-making requires reliable and accurate data and information on the status, availability, and dynamics of soil nutrients at different scales. Data and information at plot level are essential for the development of targeted fertilization plans. Information at national, regional, and global levels is required to develop policies and actions on soil fertility and fertilizer use. Over time, there have been different efforts to quantify the global soil nutrient budget (Sardans and Pañuelas, 2015; Hengl *et al.*, 2017) and the understanding of the state of the art on this matter was essential. During the parallel sessions devoted to sub-theme 1.1, the gaps and challenges to develop and obtain information on the availability (both natural and human added) of soil nutrients were identified. This sub-topic aimed to identify advances in soil nutrient budget and soil nutrients assessment.

Discussion summary

Phosphorus (P) is a critical element in soil fertility and crop production, and most P-fertilizers come from the mining of phosphate rocks, which are non-renewable natural resources (Cordell, Drangert and White, 2009). In addition, less than one percent of the P contained in soils is in a soluble, available form for plant uptake (Weil and Brady, 2017), so it is important use it efficiently and with knowledge of its reserves. Participants of the symposium presented national and regional methodologies for estimating inputs, outputs, and fluxes of P in Europe. Process-based P models (such as the DayCent model; Necpálová *et al.*, 2015) are fed with data from long-term experimental sites including different scenarios to derive P input and output information. Finer resolution approaches are reportedly under development.

Additionally, a country-driven approach to estimate the global soil nutrient budget (Global Soil Nutrient and Nutrient Budgets map [GSNmap] initiative) for mapping nitrogen (N), P, potassium (K), and associated soil properties was presented by FAO's GSP.

Soil nutrient budget trends in Cameroon, Islamic Republic of Iran, Morocco, and other 24 sub-Saharan African countries revealed low soil nutrient contents, low soil organic carbon, and fertilizer application imbalance. Various regional and global programmes were presented during the GSOIL4N. These programmes appealed to interested partners to join the nutrient budget monitoring efforts (such as WORLDSOILS, Phosphorus stocks in European agricultural soils, a global nutrient budget platform, FAOSTAT, and IFASTAT). These programmes enable countries to better monitor and report on nutrient use and nutrient use efficiency.

Conclusions

During the special session dedicated to nutrient budgeting, it was clearly established that soil fertility mapping is key to estimate a reliable nutrient budget. We need to know where the nutrients are and how to increase their content without associated externalities. Soil nutrient and fertility mapping is a powerful instrument that still needs to be developed, improved, or supported in many countries.

Updated and improved soil fertility mapping has contributed to improve food security and make agrifood systems more efficient in several countries and can potentially contribute to others, so that:

- Spatial soil variability and the variability of soil properties could be represented.
- The risks of nutrient deficiencies could be better identified and monitored.
- Global reserves of essential mineral nutrients such as P and K and other elements could be better monitored, leading to an improved understanding and management of soil nutrients.
- The design and implementation of soil nutrient management programmes and plans could be more successful.
- The success of programmes focused on crop nutritional fortification could be enhanced.

During the GSOIL4N, several gaps and challenges that hinder the development of updated, accurate, and readily available global, national, and local soil fertility maps were identified (Figure 5). Data are of particular importance for regional and national actions in

accordance with SDG Target 2.4 (sustainable food production systems, including in the context of climate change). Obtaining reliable, updated, and, above all, readily available sources of information represents one of the main challenges for the development and improvement of the global soil nutrient budget. The gaps and challenges identified for obtaining improved and updated soil nutrient data and information include:

- Data gaps regarding soil nutrient budgets for both input and outputs. The lack of accurate data hinders the derivation of information on appropriate fertilizer use.
- Large uncertainties due to data scarcity and differences in data sources and estimation methods used.
- The accuracy of many data layers remains poor in many countries.
- Persisting data gaps are difficult to fill with the current methods and the resources available.
- Collective ownership, openness, and innovation in creating novel data sourcing pipelines and analytical tools are needed to make progress on the global nutrient budget.
- The creation of a national database of spatiotemporal soil information is a challenge due to the large soil spatial variability, the influence of the wide range of farmer management practices on soil properties, the absence of digitized soil data, and the poor harmonization in soil analysis methodologies.

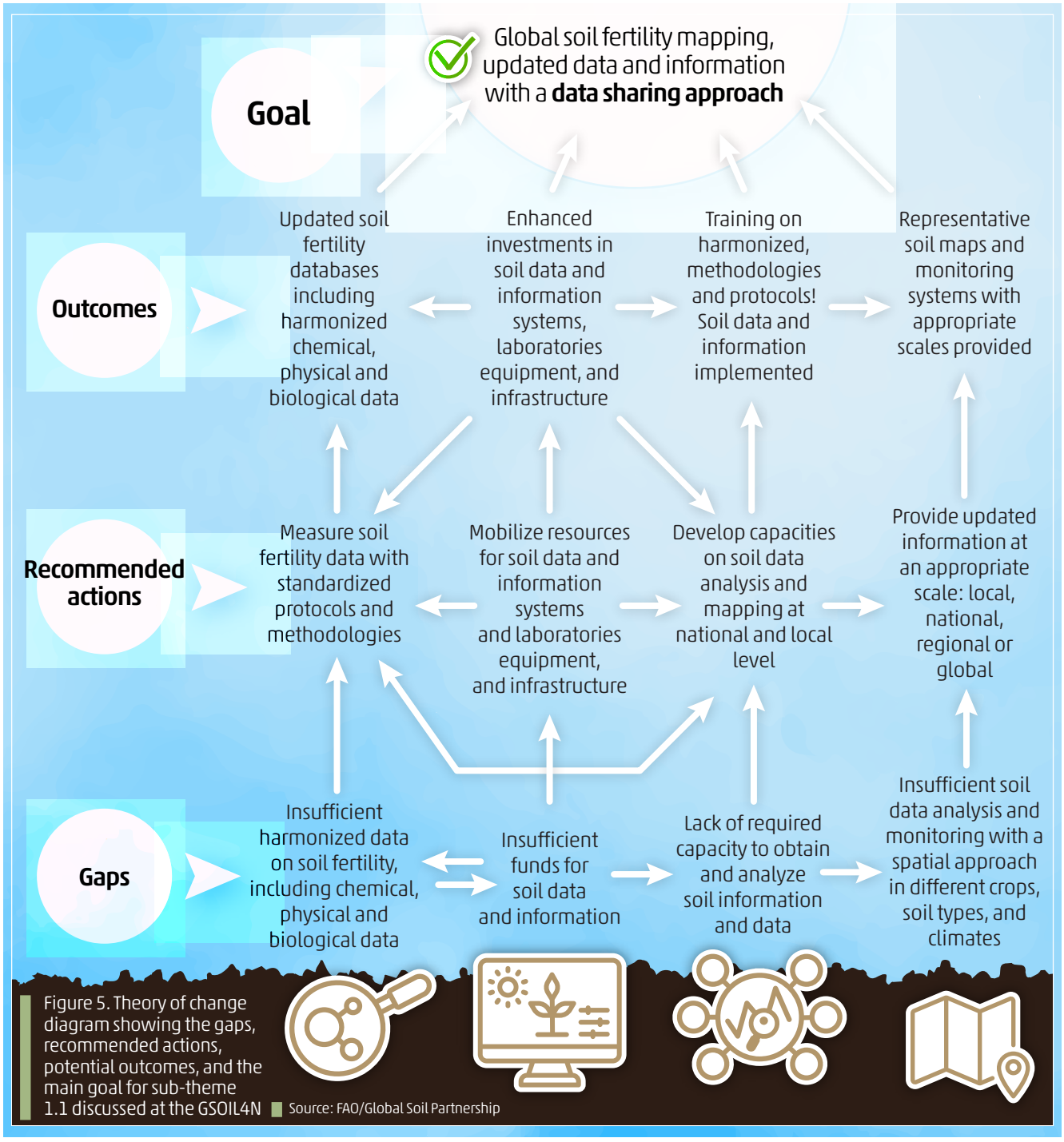

Figure 5. Theory of change diagram showing the gaps, recommended actions, potential outcomes, and the main goal for sub-theme 1.1 discussed at the GSOIL4N Source: FAO/Global Soil Partnership

Sub-theme 1.2: strategies to increase soil fertility and crop production to support food security

Healthy and well-nourished soils are key to achieve food security. A balanced supply of soil nutrients is essential to support crop yields and the nutritional value of the agrifood system (Box 1). An integrated approach of the soil-plant nutrient cycling is crucial to improve our knowledge about the system's functionality and interactions, and thereby enable better decisions on soil nutrient management while protecting the environment in a climate change scenario.

Although the production of primary crops has increased by about 50 percent in the last 20 years (between 2000 and 2020), it remains unclear how long soils can sustain this level of production (FAO, 2022b). For this reason, during the GSOIL4N the research about soil nutrient availability in different regions of the world was presented alongside the presentation of soil fertility trends and challenges, as these are fundamental to knowing how and where to strengthen soil fertility and soil nutrient management.

During the parallel sessions devoted to sub-theme 1.2, it became clear that the ability of soils to support plant growth relies on providing not only the essential nutrients, but also the adequate chemical, physical, and biological conditions. Supported by the research findings of the participants, it was well established that favourable physical, chemical, and biological soil conditions are pre-conditions necessary to achieve sufficient food production (Box 1). Throughout the event, a wide variety of strategies to improve soil fertility and crop production around the globe were discussed.

Box 1. Relevance of soil health on agricultural systems

More than 95 percent of our global food is produced in our soils by our farmers! But one third of world soils are degraded and are losing health and fertility. Countries have committed to the 2030 Sustainable Development Agenda and, with less than 10 years away, the urgent call is for actions towards a more sustainable agri-food systems for which soil health constitutes a pillar. Sustainable soil management and integrated soil fertility management should embrace nature-based solutions, management-based tools, technological tools and promote the circular economy. These strategies support enhanced soil information and monitoring systems, harmonized soil analysis protocols, fertilizer quality assessment, enhanced capacity development and the empowering of farmers to adopt good practices.

Mr QU Dongyu
GSOIL4N Opening session
Director-General of the Food and Agriculture Organization of the United Nations

Crop yields and nutritional value of food must be maintained through an adequate supply of nutrients and soil organic carbon. To meet population needs, global agrifood systems must be redesigned to be more productive, inclusive of the poor and disadvantaged communities, and environmentally resilient (FAO, 2018). As Zhang Fusuo pointed out during his keynote presentation at the GSOIL4N, "soil provides over 95 percent of food and mineral nutrition for human life. Rational utilization of soil nutrients and sustainable management strategies (green agriculture) can achieve high resource use efficiency and a reduced environmental impact", making very clear the importance of soil health in food production.

Zhang Fusuo
GSOIL4N Keynote speaker from the Chinese Agricultural University, China

In very simple and clear words, Gerda Verburg also explained that soil health is a pillar for nutrition in the world: "Soil health is as crucial for producing nutritious food, as nutrition is for children during their first 1 000 days. Just like good nutrition is the best investment in children's physical resilience, their cognitive development, well-being, and future earning power, healthy soil should be the bedrock for every country's food system. A food system that produces healthy and nutritious food in a climate resilient way is necessary for ensuring prosperity for all people involved."

H.E. Gerda Verburg
UN Assistant Secretary General and coordinator of the Scaling Up Nutrition Movement. GSOIL4N keynote speaker

Alzbeta Klein also highlighted the value of soil health explaining that "soil is the basis of all life on Earth and soil health is the foundation of sustainable food systems and food security for all. It is necessary to recognize the central role of healthy soils as an asset that is key to nutrition, economic development, climate change and resilient livelihoods, and value them accordingly."

Alzbeta Klein
Director General of the International Fertilizer Association (IFA). GSOIL4N keynote speaker

Discussion summary

During the GSOIL4N, innovative and cost-effective practices and technologies for the management and restoration of soil fertility were presented (Figure 6). The practices and strategies included:

- **Harnessing soil microbes for an improved soil fertility.** Several of the investigations presented results indicating that biofertilizers are emerging as a cost-effective and eco-friendly tool for SSM with significant positive effects on soil organic carbon stocks (Box 2). Soils increased their carbon content after the use of single microbial inoculant or different combinations of microbial inoculants. The studies presented at the GSOIL4N stressed the importance of the bio-based fertilizers as an opportunity to combine sustainable practices and create a positive soil organic carbon budget contributing to soil organic carbon sequestration. Positive synergies of biofertilizers with leguminous crops lead to a more pronounced increase in soil organic carbon content. Plant microbiomes and the development of tools for SSM based on soil microorganisms were also presented as a valid alternative to the use of chemicals in the control of plant pathogens. Optimizing plant nutrition through pre-sowing inoculation of seeds with microbial preparations based on nitrogen-fixing and phosphate-solubilizing bacteria was presented as an alternative tool to increase crop yields and minimize the use of mineral fertilizers, as well as to prevent soil and environmental pollution.
- **Pulses and agrobiodiversity to boost soil fertility.** The combination of different nature-based solutions leads to positive results in terms of soil fertility and overall soil health. Plant associations such as intercropping system or cover crops including various leguminous species improve soil health, microbial activity, SOM content, and soil moisture retention, supporting food security.
- **New sources of nutrients to increase soil fertility.** New solutions that allow for the recycling and reuse of nutrient sources were proposed. It was reported that waste recycling sources such as coffee grounds and industrial waste stimulated growth of the soil microbial biomass and increased soil organic carbon mineralization. In addition, the advantages of the use of environmentally friendly materials such as biodegradable mulch films compared to conventional plastics films were also discussed. The results indicated that using biodegradable plastics does not significantly affect soil quality and reduced plastic wastes at the end of the crop cycle.
- **Integrated crop nutrients and soil management.** Integrated nutrient management includes the use of mineral and organic fertilizers and soil amendments. Related studies presented clearly showed the significant improvement of soil fertility, along with an increase in crop production. However, to achieve a higher nutrient use efficiency (NUE), participants highlighted the need to consider the following factors:
    - the 4 R approach for fertilizer application (use of the right source, at the right rate, right time and right place);
    - the role of data-driven nutrient management, based on soil analysis and nutrient crop demands; and
    - the balance of the input of nutrients (organic and inorganic fertilizers and soil amendments).

Some examples showed that the three principles of conservation agriculture (minimum mechanical soil disturbance, soil cover with crop residues and cover crops, and species diversification) supported the improvement of soil structure, water regime, nutrient budget, and microbial community.

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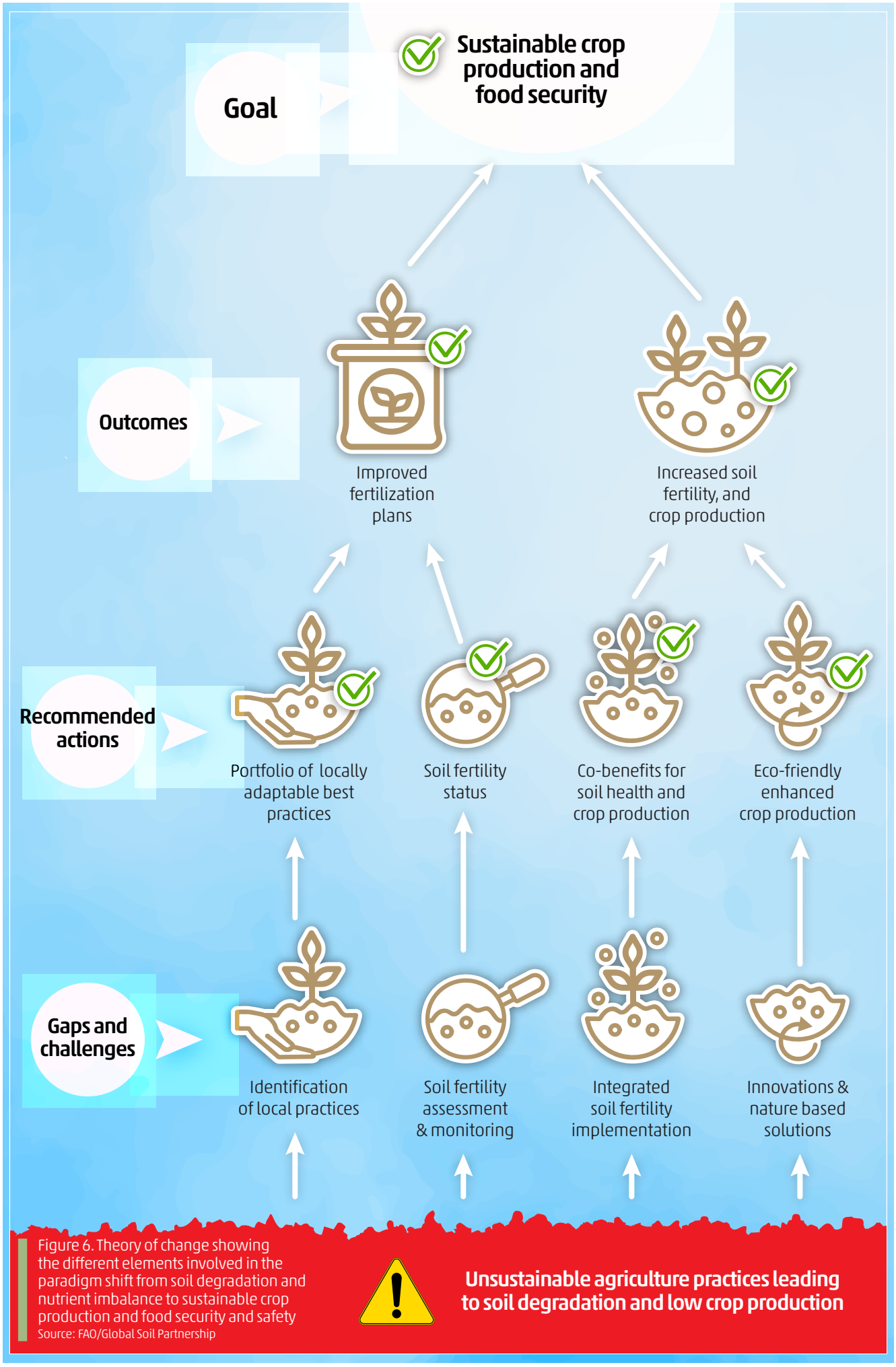

Figure 6. Theory of change showing the different elements involved in the paradigm shift from soil degradation and nutrient imbalance to sustainable crop production and food security and safety
Source: FAO/Global Soil Partnership

Conclusions

Backed by solid evidence, soil microbes are a crosscutting solution shown to sustainably increase soil fertility and reduce the mineral fertilizer input. **Biofertilizers and biostimulants are promising solutions to increase or optimize soil nutrients.**

The soil microbiome is a key player in increasing nutrient availability, and plant and soil protection:

- Soil microbes improve key ecological functions in agroecosystems, such as increasing water availability, soil carbon sequestration, enhancing the bioavailability of nutrients, producing fertility hot-spots, and increasing soil resilience to climate change.
- Microbial diversity in the rhizosphere increases the crop system resilience to extreme environments.
- Soil engineers, especially termites and earthworms, significantly improve key ecological functions. Their activities stimulate microbial decomposers, leading to increasing degradation rates of SOM, which is in turn is positively related to carbon and nutrients release.

The combination of these strategies optimizes results. The replenishment of soil resources through integrated nutrient management uses a minimum effective rate of balanced quantities of organic and inorganic fertilizers, in combination with specific microorganisms and is a hugely promising practice. It supports the maintenance of higher productivity and greater stability of crop production, while reducing environmental pollution.

The gaps and challenges identified for the adoption and implementation of integrated nutrient management practices to increase soil fertility include:

- a lack of awareness, education, standard tools, and infrastructure for nutritionally-balanced farming practices;
- a poor understanding of the complex nature of plant-nutrient dynamics under variable soil composition; and
- limited information regarding the value of organic waste and industrial waste as a potential fertilizer, despite the strategic importance of recycling waste to improve soil fertility and agricultural production.

Box 2. Plenary panel "Innovations for soil fertility management"

In addition to ongoing global challenges such as poverty, malnutrition, environmental pollution, and climate change, other threats have arisen that exacerbate food insecurity and environmental degradation, including the COVID-19 pandemic, war, and rising fertilizer prices (FAO, IFAD, UNICEF, WFP and WHO, 2022). These place humanity in a "perfect storm" scenario for which we must take quick action. Recovery from the current crisis will require an unprecedented and collaborative effort by countries to rebuild the economy, strengthen crop production and support farmers. In times of crisis, innovation is key to providing effective and environmentally friendly solutions to recover and increase soil fertility while avoiding externalities like pollution and climate change.

During the GSOIL4N, a panel of experts in soil nutrition discussed different perspectives and strategies to increase and preserve the fertility of agricultural systems. The panellists agreed that SSM is still the most cost-effective solution to increase macro and micronutrient content in soils. The development of better, cleaner technologies for food production must be a priority in the short-term.

Highlights:

- Biofertilizer technologies and microbiome-based management:
  - The most promising innovations to improve micronutrient availability are associated with use of soil microorganisms.
  - Biofertilizers are an innovative, eco-friendly, and effective alternative to improve plant nutrition and soil health. For the successful adoption and implementation of biofertilizers in the future, the complexity of the microbiome must be recognised, as microorganisms are not alone and depend on the interaction with their surrounding environment, which can modify their performance.
- Biostimulants: Opportunities and challenges to increase soil fertility:
  - Biostimulants are a support that can significantly and sustainably improve crop production and soil health by acting on natural processes in plants and soils to improve plant nutrient availability and uptake.
  - The evaluation and monitoring of the quality and safety of alternative nutrient sources such as biofertilizers and biostimulants is essential for their adoption without risks to develop environmental and human health problems.
- Soil fertility mapping for guiding fertilizers recommendation:
  - Emphasis on agronomic tests, farmers' practices and soil nutrient management are key factors for the successful increase in crop production.
  - There is no single solution to all problems of agricultural production. The combination of different fertilization strategies adapted to local conditions and crops usually gives the best results.

Mr Amit Rastogi
Coromandel International Limited, India

Mr Prem S. Bindraban
International Fertilizer Development Center, Ghana

Ms Micaela Tosi
University of Guelph, Canada

Mr Antonis Angeletakis
European Biostimulants Industry Council, United Kingdom of Great Britain and Northern Ireland

Mr Aniss Bouraggadi
OCP Group, Morocco

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Theme 2: sustainable soil management for food security and better nutrition

Food quality, which includes the safety and nutritional value of food products, is a pillar for food security. Healthy soils provide enough macro and micronutrients to support plant nutrition (Schjoerring, Cakmak and White, 2019). Plants supplied with balanced and sufficient nutrients grow optimally and are more resilient to pest and diseases. In contrast, soil macronutrient and micronutrient deficiencies limit plant health, crop productivity, and the nutritional quality of food, ultimately affecting nutrition and human health (Sanchez and Swaminathan, 2005). The chronic lack of micronutrients derived from nutrient-deficient soils and crops can cause severe but often invisible health problems, especially among women and children (Black *et al.*, 2013), known as "hidden hunger". Over 2 billion people worldwide suffer from iron (Fe), zinc (Zn) and other (multiple) micronutrient deficiencies (WHO, 2016). The problem is most severe in low- and middle-income countries, especially in Africa where the estimated risk for micronutrient deficiencies is high, since more than 50 percent of the population suffers from moderate or severe food insecurity (FAO, IFAD, UNICEF, WFP and WHO, 2021).

Although hidden hunger is a multifactorial challenge, adequate soil nutrient content plays a determinant role in combatting this problem. The nutrition-sensitive agriculture approach addresses soil fertility and crop nutrition in an efficient, inclusive, and sustainable manner since it focuses on the implementation of diversified farming systems aimed at the production of high-quality nutritional food to overcome malnutrition and micronutrient deficiencies (Figure 7).

Soil nutrient availability is linked to soils' physical, chemical, and biological properties. Efforts and investments focused on increasing plant nutrient uptake and content can be lost if soils are not healthy. Soils that are compacted, eroded, nutrient- and soil organic matter-depleted, contaminated, acidified, or that present salinity problems, cannot produce plants containing nutrients necessary for human health, or able to assimilate nutrients added by fertilizer application.

During the GSOIL4N, the links between soil micronutrient content and human health were discussed, and different pathways for nutrition-sensitive agriculture were explored as a mechanism to increase the nutritional quality of food. Among these pathways, innovation on SSM and soil fertility emerged at the different fora of the symposium. The spatial distribution of micronutrient deficiencies was also a major point addressed.

Discussion summary

Iron, Zn, and vitamin A are among the micronutrients identified by the World Health Organization (WHO) as most lacking in diets globally. These deficiencies start in soils when they are nutrient depleted by natural or human induced causes. One of the main goals of the GSOIL4N was to unveil strategies to improve soil nutrient content and food quality, with a special focus on micronutrient deficiencies.

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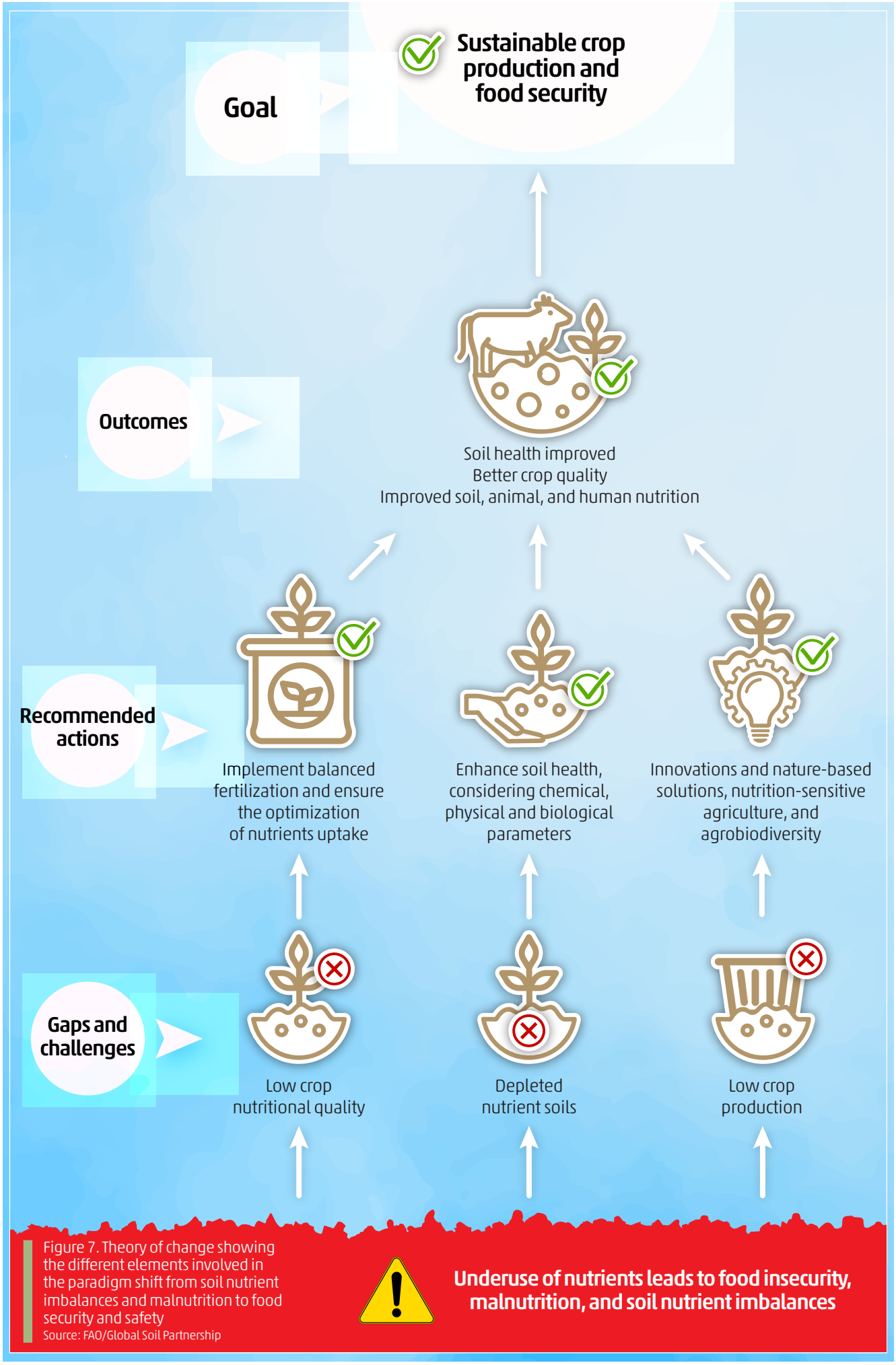


Figure 7. Theory of change showing the different elements involved in the paradigm shift from soil nutrient imbalances and malnutrition to food security and safety
Source: FAO/Global Soil Partnership

Biofortification and soil fertility in Africa

Africa is undoubtedly the region of the world that most urgently requires immediate action to combat nutritional deficiencies in soils, humans, and animals. Different strategies that have contributed to solving this problem were presented. For example, a study of the link between soil adsorption and desorption mechanisms with grain Zn concentrations and uptake by teff, wheat, and maize in different landscape positions in Ethiopia was presented. Novel fertilizer strategies to biofortify Zn concentration in wheat grains, and foliar Zn fertilization in soybean were also explored.

The factors driving plant responses to biofortification were discussed. Together with SSM, biofortification can be beneficial for human nutrition and favour nutrient cycling and especially with the association or rotation of diverse species (including pulses) (Box 3). More nutritious varieties of staple crops that provide higher amounts of nutrients are part of an integral solution to nutrient deficiencies. Field position and crop management were key factors determining the nutritional quality of biofortified maize in Zimbabwe. Successful examples of selenium (Se) biofortification of staple crop to fight hidden hunger in Malawi were also discussed.

Biofortification has proved to be an effective strategy to increase Zn, Fe, and Se. Combined with other SSM practices, biofortification has contributed to crop nutrient deficiency alleviation. Agronomic biofortification can be influenced by micro and macronutrient fertilization, so therefore, integrated approaches are essential to optimize the results.

Micronutrient geospatial distribution

Participants highlighted that improved knowledge of the spatial location of soil macronutrients and micronutrients as essential to overcome global nutrient imbalances. There has been progress in the monitoring of the spatial variability of micronutrients and build capacity on micronutrient deficiency surveillance in Malawi and Ethiopia. Local-scale soil sampling in Zimbabwe will bring a valuable insight into the relationship between hidden hunger and soil micronutrient content. Although spatial variation in soils micronutrient content is related to human nutrition, other factors such as gender impacts the efficiency of biofortification programmes, as has been shown in Zimbabwe. Landscape position also evidenced different responses to micronutrient fertilizer on agronomic fortified crops in Ethiopia.

Soil microbes to improve micronutrient availability

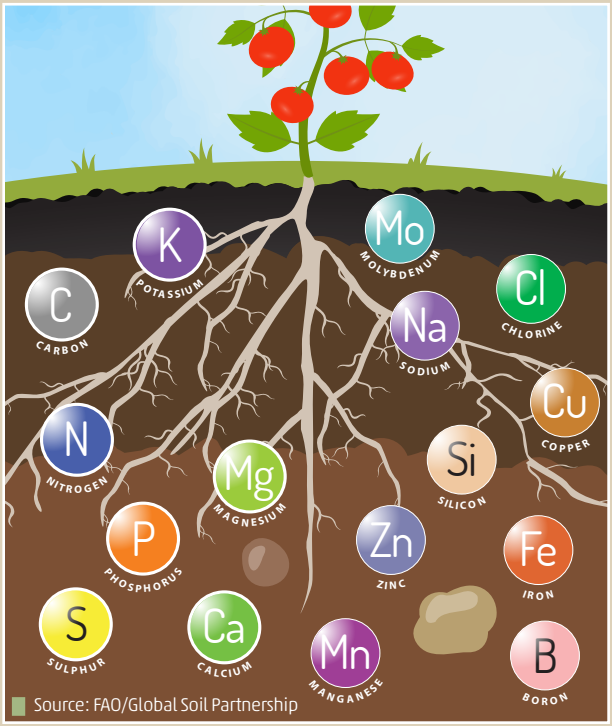
During the GSOIL4N, the boosting effect of soil microbes on soil fertility and soil health was extensively documented. Evidence that microbes are key players in micronutrient availability in soils and plant nutrient uptake was also presented. It was shown that innovative approaches integrating nutrient management, rhizobacteria, and biofortification can lead to a significant improvement and conservation of soil fertility and crop health. The biofortification of rice with Fe and Zn using indigenous micronutrient mobilizing beneficial rhizobacteria has led to an alleviation of Zn deficiency.

Box 3. Soil micronutrient supply and biofortification

Biofortification is a process of increasing the density of vitamins and minerals in a crop through plant breeding and other agronomic practices, so that the biofortified crops, when consumed regularly, generate measurable improvement in vitamin and mineral nutritional status (HarvestPlus, 2022). An adequate soil nutrient management in combination with biofortification approaches can act synergistically for better results, as appointed by Grace Kangara during the GSOIL4N keynote conference:

"Understanding of factors governing soil micronutrient supply, their exploitation, and a complementary suite of innovative agronomic biofortification technologies is key towards improved human and livestock nutrition, and conservation of the soil resource base."

Grace Kangara
GSOIL4N keynote speaker
Rothamsted Research, United Kingdom of Great Britain and Northern Ireland



Source: FAO/Global Soil Partnership

New approaches for studying soil micronutrients

Fertilizer use efficiency is not exclusively needed for macronutrients. Advanced strategies for studying the assimilation of micronutrients were discussed. Isotopic techniques can be used to investigate chemical synergies and antagonisms among micronutrients as in the case of sulphur (S) and Se competition for ryegrass uptake.

Innovation came up as a pillar to alleviate plant, soils and human nutrient deficiencies, and nanotechnology plays a significant role in this. The use of cobalt-ferrite nanoparticles is also under investigation as an alternative fertilizer for the agronomic iron fortification of staple grains. Synergies and antagonisms are of relevance for micronutrient fertilization plans and innovative approaches as nanotechnology and isotopic techniques can be important in unravelling mechanisms ultimately driving micronutrient plant uptake.

Synergistic effects constrain micronutrient availability and use efficiency

Plant physiological and soil chemical and biological processes can affect micronutrient fertilizer use efficiency. The study of soil micronutrient availability remains a challenge because of the large variation of results showed in terms of nutrients deficiency or crop yields, correlated with soil properties (such as clay content and soil organic carbon), field position, and crop management. Soil degradation severely hampers the success of plans and strategies aimed at improving the nutritional content of soils and crops.

Soil micronutrient enrichment faces barriers as does any other fertilization plan. These barriers are caused by synergies with soil degradation problems such as salinity and acidity, and can become major constraints to fertilization strategies. Micronutrient constraints in sodic soils of India and the silicon bioavailability and fate in acidic, neutral and alkaline soils were also discussed (micronutrients imbalances in sodic or acidic soils are strongly influenced by pH and cation exchange capacity).

Conclusions

Visibility and recognition were given to hidden hunger and the factors that regulate it in production systems. After the sessions dedicated to theme 2 of the GSOIL4N it was clear that nutrition-sensitive agriculture is a multifactorial approach that requires the involvement of several stakeholders, from farmers and NGOs to private sector and governments. Different perspectives were heard, especially at the plenary expert panel *Sustainable soil management and biofortification: allies to combat malnutrition* (**Box 4**).

Another expected outcome of the discussions on theme 2 was the improved understanding of how the adoption of SSM can produce nutritious food to fight malnutrition and contribute to human wellbeing. In this regard, it was emphasized that Zn and Se are among the main micronutrients required in the soils to provide healthy food. Especially because of the major role Zn can play to cope with Covid-19 effects. Agronomic biofortification, nutrient enhancement of staple crops, and SSM represent a cost-effective tandem for food security.

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Box 4. Plenary panel Sustainable soil management and biofortification: allies to combat malnutrition

Soils with degradation problems are unfit to produce plants that contain nutrients necessary for human health and cannot assimilate nutrients added by the application of fertilizers (FAO, 2015). Sustainable soil management is essential to preserve and increase nutrient content in soils, plants, animals, and humans. Different SSM approaches, including the association or rotation of diverse species, pulses (FAO, 2016), and biofortification, can be beneficial for human nutrition and favour nutrient cycling (Scientific Panel on Responsible Plant Nutrition, 2020). A group of experts from academia, global food programmes, and governments identified the essential elements and soil health key drivers to be considered and paired with other strategies for food security and nutrition.

Highlights:

- An integral approach to support food security is to connect people's deficiencies with those of the soil, and in turn link them to their spatial occurrence and to the physical, chemical and biological soil properties.
- Crop and soil deficiencies assessments have mostly been conducted in Africa. However, research, fertilization plans and strategies to overcome hidden hunger should be comprehensive and other regions should be included.
- Biofortification can improve the global food system by increasing the nutrient content of staple grain crops to bridge the gap between agriculture and nutrition. The results of biofortification programmes can be enhanced with the combination of SSM.
- Synergies should not be overlooked since they can be an effective path to boost the results of fertilization programmes. A balanced addition of micronutrients to soils can improve the effectiveness of chemical fertilizers. The combination of soil organic matter with micronutrients contained in mineral fertilizers is also a keystone of soil fertilization.
- Governance and capacity development are key to downscaling nutrient soil and crop enrichment programmes and to raise awareness about the connection between depleted-nutrient soils and nutrient deficiencies in plants and people.

Mr Martin Broadley
Rothamsted Research, United Kingdom of Great Britain and Northern Ireland

Ms Jenny Walton
Harvest Plus, United States of America

Ms Carolina Olivera
Global Soil Partnership, FAO

Mr Mamoudou Traorè
National Soil Survey Office, Burkina Faso

Mr Md Kamaruzzaman
Soil Resource Development Institute Bangladesh

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Theme 3: impacts of soil nutrient management on the environment and climate change

Soil nutrient imbalance is caused by the underuse, misuse, and overuse of nutrients contained in fertilizers and other nutrient sources (FAO, 2017; 2019). Nutrient imbalance induces some soils to be nutrient-depleted, reducing or losing their capacity to support crops, while others have such a high nutrient concentration that they represent a toxic environment to plants and animals, or are sources of GHG emissions (FAO, 2017) (Box 5). However, the optimization of mineral and organic fertilizer use can help reduce soil, water, and air pollution, and even reduce GHG emissions contributing to climate change mitigation.

The GSOIL4N aimed at setting the principles of a global agenda for a sustainable use and management of fertilizers to improve soil fertility in an environmentally friendly way. Additionally, the symposium also served to identify innovative nutrient sources and management practices and promote more efficient fertilizers and fertilization strategies. As different nutrient sources are used under several soil types, climates, and crops, it was therefore necessary to critically analyse the impact of mineral and organic fertilizers on soil ecosystem functioning to identify the more sustainable environmental cost-effective soil management practices.

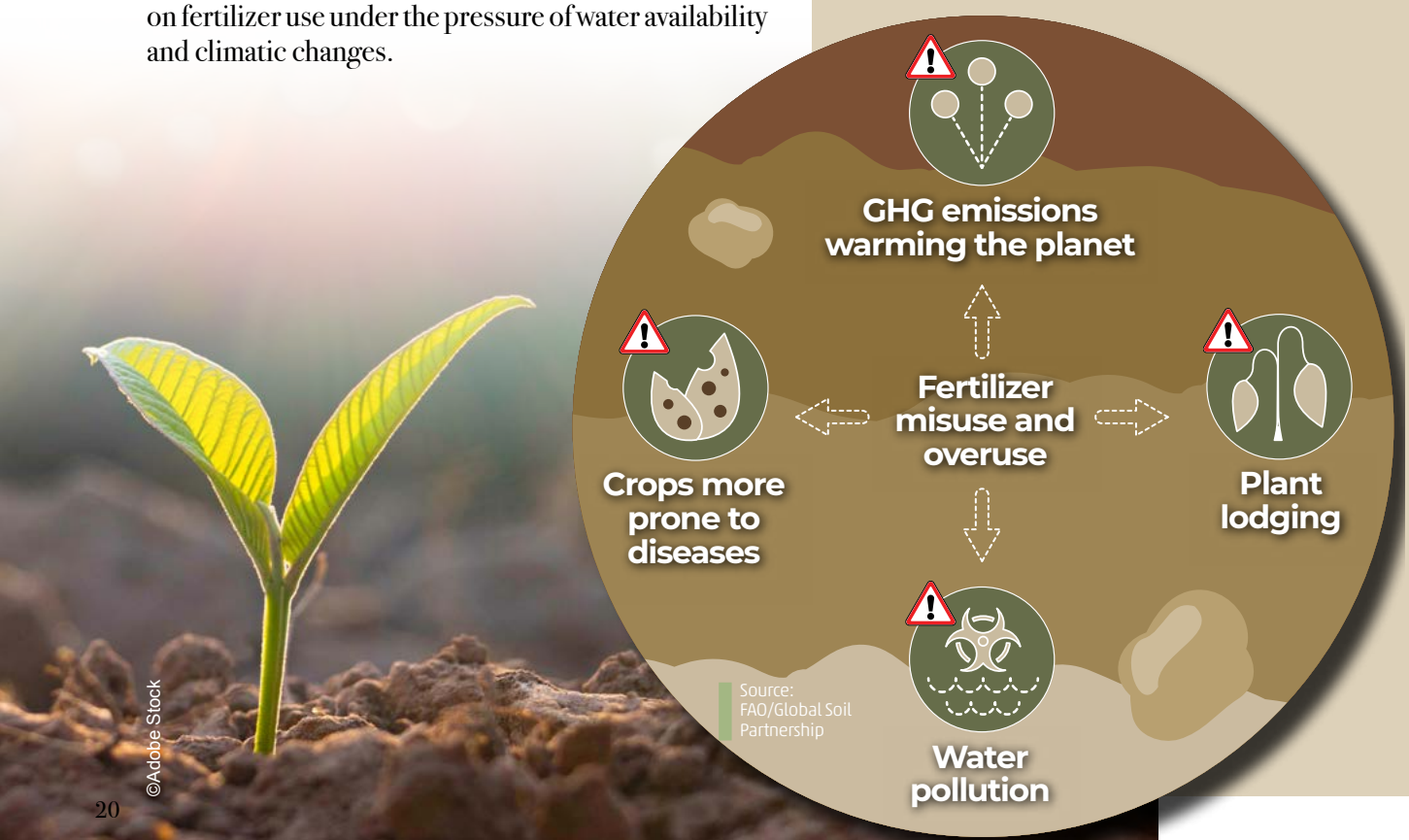
It was also crucial to advocating an agenda for action on fertilizer use under the pressure of water availability and climatic changes.

Box 5. Global effects of nutrient imbalances

Nutrient imbalances derived from unsustainable crop practices have severely modified global biogeochemical cycles of P and N, leading to environmental pollution and exacerbating climate change (Steffen *et al.*, 2015). Agricultural activities are responsible for 12 percent of annual anthropogenic GHG emissions worldwide (Tubiello *et al.*, 2015). About 38 percent of these emissions result from the release of soil nitrous oxide (N_2O) from synthetic fertilizers, manure, and crop residues, and 11 percent from methane (CH_4) in rice cultivation (Tubiello *et al.*, 2015). Nitrous oxide and CH_4 are very powerful GHGs capable of heating the planet with a force 298 and 23 times greater than that of CO_2. Once they reach the atmosphere GHGs can remain there for about 112 years in the case of N_2O, and 12 years in the case of CH_4, warming the planet, polluting the air, reducing stratospheric ozone, and affecting human and animal health (Houghton *et al.*, 2001).

Nutrient leakage from agricultural land represents economic losses. The loss of agricultural fertilizer resources is worth approximately USD 200 billion annually (Sutton *et al.*, 2020). The costs for human health and the impact on aquatic and terrestrial ecosystems amount to between USD 400 and 4 000 billion annually due to N overuse and misuse (Sutton *et al.*, 2020). As Johan Rockström stated in his keynote presentation: "Global land-use change, soil moisture variability, and application of N and P fertilizers have transgressed planetary boundaries, levels defining safe operating space for humanity, thus undermining the biosphere's capacity to withstand anthropogenic disturbance and jeopardizing future Earth system stability. To return into Earth's safe space, a radical global food system transformation is necessary."

Johan Rockström
GSOIL4N keynote speaker
Potsdam Institute for Climate Impact Research, Germany



Discussion summary

During the symposium, various gaps in knowledge and challenges affecting soil fertility were presented, as well as solutions offered to optimize the use of nutrients in agricultural systems.

Fertilizer use efficiency. The loss of nutrients from the plant-soil system leads to environmental, health and economic losses. Fertilizer use efficiency is a cost-effective preventive approach to combat the impacts of nutrient imbalance (Figure 8). The following approaches for increasing fertilizer use were discussed:

- Composted municipal solid wastes. There was evidence provided that composting not only helps to clean the environment but also provides a soil amendment (compost) which will in turn lead to soil vitalization.
- Mixed application of compost and inorganic fertilizers. The latest research showed that maize yield was increased by combining organic and inorganic fertilizers. The combinations reduced the emission of N_2O while CO_2 and CH_4 emissions were less affected.
- Upcycling animal manure by the implementation of innovative and integrated nutrient recovery. Examples of this are on-farm experimental pilots, producing a liquid concentrate rich in NPK, organic matter and reclaimed water.
- Root traits that improve soil structure and optimize nitrogen cycling. The identification of potential target genes in the crop genome that influence soil microbial biomass could be used to develop breeding targets in crops. This would contribute to improving the efficiency of use of N-fertilizer by crops, while reducing N losses to the environment.
- Dynamics of soil nutrients in coffee crops. The shade tree species in the coffee production system influence the dynamics and availability of nutrients, as well as the concentration of soil organic carbon and SOM, reducing GHG emissions.
- Neem materials and biochar as nitrification inhibitors reduce nitrate leaching. The reduction in the amount of nitrate leaching in sub-Saharan ferric Luvisol by using (sawdust) biochar and neem seeds resulted in a higher agronomic performances of maize crops.

The state of soil fertility in the presence of different contaminants:

- **Plastics**. Several studies found a decrease in soil bacteria richness and diversity, with the bacteria more affected than fungi in soil contaminated by plastic mulches. The use of bacteria able to biodegrade microplastics was reported as an alternative for soil bioremediation. Future research needs to clarify the impact of plastics on key microbial species and activities that are critical to major soil functions.
- **Heavy metals**. The activity of radio-caesium in contaminated soils decreased by using potash fertilizers in a complex with liming. Lead-contaminated soil improved through precision farming, differentiated use of ameliorants and micro fertilizers or by using a magnetic nanomaterial $SiO_2Fe_3O_4$ C-COOH as a lead immobilizer.

Excess of nutrients:

- Intense agricultural and livestock activities dramatically increased the organic P fraction in soil and in lake sediments. The reduction of P sources in the diet of animals is a new method of recycling animal manures rich in P, and the use of crops or species with high rates of P uptake could provide a solution for soil.
- Phosphorous overuse (phosphate fertilizers) increased the content of mobile forms of fluorine and heavy metals in Chernozems due to a decrease in soil pH and the high buffering capacity of this type of soil.
- Lead-contaminated farmland soil was repaired by applying solidification with conventional soil lead passivation agent.

Extra-heavy crude oil:

- Extreme toxicity condition of soil polluted with petroleum by-products could be reduced with bioremediation techniques using a grass (*Chrysophogon zizanioides*).

Water availability and climate change

- Aridity generates problems that seriously affect soil fertility and make it almost impossible to implement strategies to improve soil health and fertility. Floods also have adverse effects on soil fertility and enhance GHG emissions. Implementing strategies for water management is essential and that is why next year this will be the theme of the global symposium.

It is also important to note that poverty and the increase of fertilizer prices together with social conflicts present the perfect storm for fertilizer unaffordability and inaccessibility for many farmers, further widening the gap between soil degradation and food insecurity.

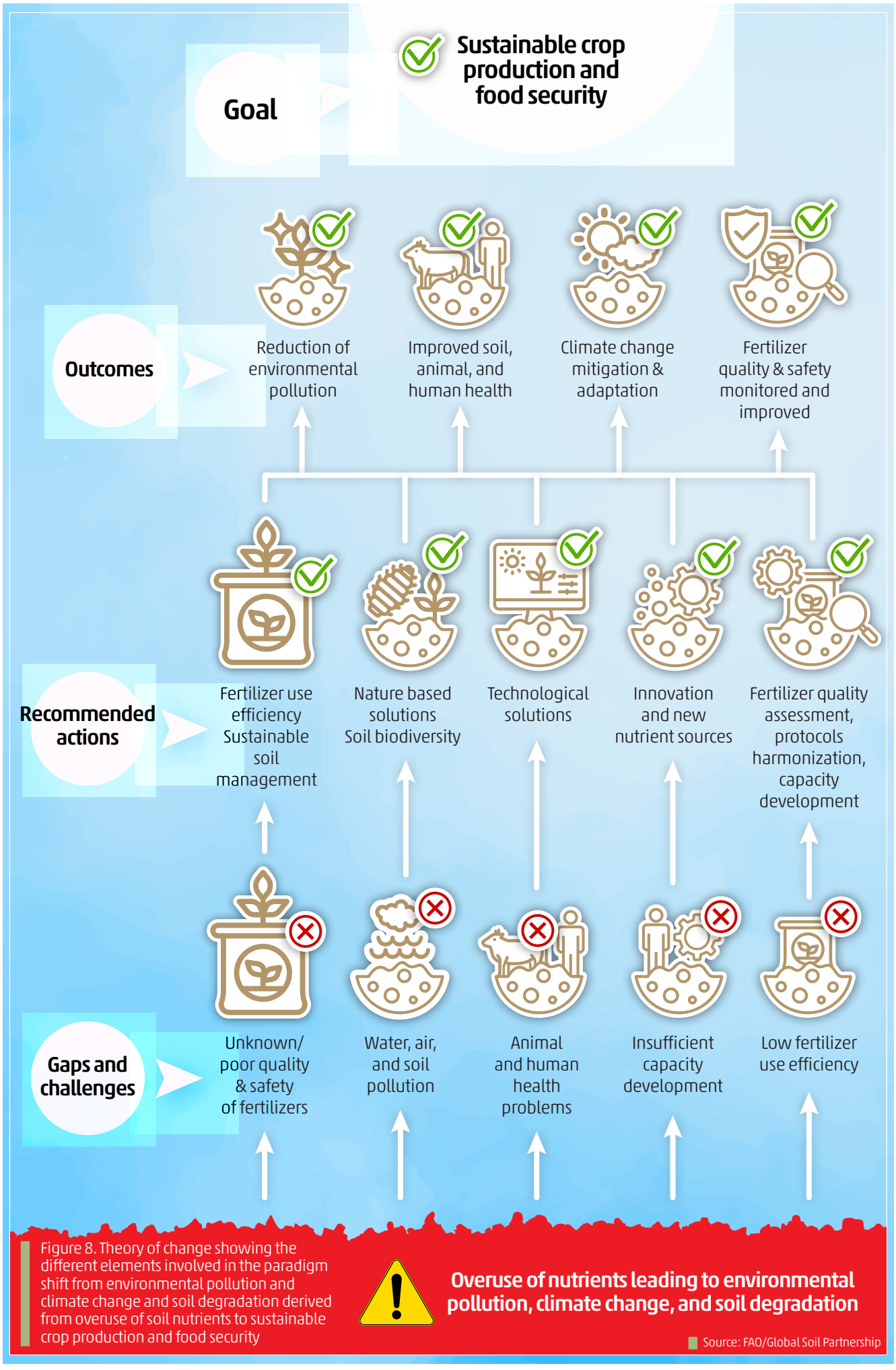


Figure 8. Theory of change showing the different elements involved in the paradigm shift from environmental pollution and climate change and soil degradation derived from overuse of soil nutrients to sustainable crop production and food security

Conclusions

Food production needs are increasing while the productivity of agricultural land is decreasing worldwide, so it is necessary to find sustainable solutions to enhance soil fertility while maintaining environmental equilibrium. Evidence has shown that the use of composted organic materials, the combining of organic and mineral fertilizers, and fertilization based on soil nutrient availability and crop demands offer a way to prudently produce and use fertilizers, and reduce GHG emissions at the same time.

Soil pollution is also a hugely important topic that must be urgently addressed. The research presented at the symposium indicated that contaminants (such as heavy metals, petroleum hydrocarbons and plastics) together with the excess of nutrients, are now affecting soil ecosystem functioning, soil biodiversity and consequently nutrient cycles and soil fertility. Petroleum hydrocarbons and plastics also represent a problem that needs to be tackled.

Diagnosing soil fertility, monitoring soil health status and degradation processes, assessing crop sensitivity and irrigation water, and the quality of fertilizers are the key to determining effective fertilizer management strategies.

Bioremediation and phytoremediation can also be an affordable and sustainable solution to the recovery of polluted soils.

Organic amendments by using compost, vermicompost, digestate or other organic sources as fertilizers are cost-effective strategies for decreasing the degradation of fertility in agriculture land worldwide.

Box 6. Plenary panel Integrated soil fertility management: looking ahead

Misuse and overuse of fertilizers lead to nutrient losses to the environment. Once nutrients such as N and P exit the crop system, it is very likely they will act as contaminants and as climate change drivers and cannot be easily returned to soils. Therefore, the most cost-effective and feasible approach to reducing GHG emissions, water contamination, and soil degradation is prevention. A preventive approach entails the adoption of specific practices and the use of different tools to improve nitrogen use efficiency and judicious use of fertilizers. These strategies and tools include nature- and technology-based solutions, as well as SSM approaches. Four experts provided an insight into the wide array of alternatives to optimize nutrient use at this GSOIL4N plenary panel.

Highlights

Integrated soil fertility management (ISFM):

- Agronomic use efficiency needs to be maximal for environmental and economic reasons, and ISFM is central to achieving this goal.
- The pillars for ISFM are the correct management of fertilizers, the application of good agronomic practices, the use of locally-adapted crop varieties, the combination of mineral and synthetic fertilizers with organic inputs and other alternative sources, and to address local constraints (such as climate, soil variability and status) and local concerns.

Soil microbes to enhance soil fertility:

- The role of microbes in enhancing soil fertility is unquestionable and is emerging stronger than ever as leading a "micro green revolution". Plant growth-promoting organisms, biofertilizers, and nitrogen-fixing bacteria, can partially replace, fully replace, or optimize the use of mineral fertilizers.
- The combination of microbial processes and co-inoculation boosts benefits for soil fertility.

Models and technological tools to improve fertilizer recommendations:

- Nitrogen is the most critical nutrient used in cropping systems worldwide, but the misuse and overuse lead to multiple environmental and health problems.
- There are plenty of N management tools that could be used to help improve fertilizer recommendations while reducing reactive N losses to the environment.

Status and challenges of P reserves for agriculture:

- Phosphorus is crucial in agricultural production but most P-fertilizers come from non-renewable and finite mineral sources. Although latest findings showed that P reserves will endure in the long-term, mineral P fertilizers should be efficiently used to cope with high mineral fertilizer prices and restricted availability to farmers. In parallel, innovations to help solubilize the P contained in soils have a relevant role to support farmers in taking advantage of the P already present in soils.
- Further studies and updating of information are needed to avoid misinformation about global P budget.

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General conclusions of GSOIL4N and recommendations

The symposium brought together more than 9 000 participants from various regions of the world, representing diverse perspectives on soil fertility, soil management, soil degradation, nutrition, and possible solutions and expectations for a better future. Despite the divergence of issues and challenges, the participants came together with a firm purpose: better nutrition for all without leading to damage to the environment and to our health.

We have realized that in the search for more and better food, we have endangered both our survival and that of other species on the planet. We have modified planetary processes, leading to nutrient imbalance that in turn derives from unsustainable agricultural practices. Nutrient imbalance leads to consequences for crops, animals, humans and the environment. The loss of soil fertility and nutrient imbalance are challenges that become a perfect storm, co-occuring with social, economic, environmental and health problems. During the GSOIL4N, it became clear that although we are facing a colossal and highly complex challenge, it is still possible to find a way through, but comprehensive solutions are required. The One Health approach emerged as the best solution, although soil health should be recognized as a central part of it, and its sustainable management a potential solution.

Participants, keynote speakers, and panellists agreed that integral and holistic approaches are needed to combat malnutrition, soil degradation and fertility loss, environmental pollution, and climate change. **Sustainable soil management is still the most cost-effective, environmentally friendly, affordable, and feasible strategy to achieve sustainable food production**.

Another important conclusion was that **soil microbes and nature-based solutions are the most promising solutions to tackle nutrient imbalances and their consequences**, and additionally represent a vehicle for unlocking multiple benefits for soils, crops, animals, and humans. Perhaps one of the strongest agreements during the GSOIL4N was the high expectations on innovations. New and alternative sources of nutrients come with significant and immediate benefits for crop production and the environment, since they are low carbon, efficient and support a circular economy.

Participants agreed that farmers are very often not aware of the composition of fertilizers. Moreover, many farmers are not using fertilizers based on expert recommendations (which are based on crop requirements and soil fertility status). **Soil nutrient budgets and fertilizer quality assessment are central to addressing their correct use and preventing environmental pollution. Therefore, the quality assessment of all nutrient sources is a necessity that can no longer be postponed.**

No fertilization plan or SSM practice can be possible if there is no updated, accurate and available data and information on soil fertility and soil nutrient budgets. One of the most important factors in combating food insecurity, climate change, and environmental deterioration is the joint work of countries to overcome nutrient imbalances. The foundations for this were laid during the GSOIL4N.

Recommendations

Recommendation 1. Map and monitor soil nutrients and soil fertility and deepen the knowledge about soil nutrient budget.

The following measures are recommended:

- **Develop country-driven global soil nutrient and nutrient budget maps.** Soil nutrient mapping and monitoring are powerful instruments that that can greatly benefit agriculture by identifying areas that have a deficiency or surplus of essential nutrients. However, it is important to note that these tools need to be developed, improved, and supported to ensure its effectiveness, reliability and adoption.
- **Map and monitor soil fertility in a broader perspective by also considering the physical, chemical, and biological soil properties.** Soil fertility is not only determined by the availability of soil nutrients but by the combination of other factors such as physical, chemical, and biological properties of the soil. Mapping and monitoring these properties ensure that soil fertility measurements are comprehensive.
- **Support countries with capacity development for conducting soil nutrient budget maps and national soil information and monitoring systems.** Country-driven approaches require robust national soil information and monitoring systems with standardized and harmonized data and comparable methodologies from soil sampling to laboratory analyses and interpretation results.
- **Advocate for a global approach to facilitate the collation and availability of soil fertility data and information.** The availability of soil fertility data and information is a prerequisite for estimating the global nutrient balance and currently represents the main barrier preventing the characterization of soil fertility status. Collaboration and collective data-sharing through open access and community-led initiatives are crucial for overcoming this barrier.

- **Adopt a holistic approach that considers all aspects of soil nutrient inputs and outputs.** This approach should include erosion, greenhouse gas emissions, leaching and runoff. Failing to account for critical nutrient outputs in budget estimations increases the likelihood of misleading information about soil fertility and the factors that control it at both national and global levels.

Recommendation 2. Develop innovative approaches and alternative products to optimize soil nutrient content, enhance fertilizer use efficiency, and reduce externalities associated with soil fertility management.

The following measures are recommended:

- Promote the wide adoption of the International Code of Conduct for the Sustainable Use and Management of Fertilizers.
- Shift the paradigm from the environmental impact of mineral and inorganic fertilizers to improved efficiency and alternative nutrient sources.
- Find new nutrient sources and support the adoption of the existing ones. New nutrients sources should be more affordable, environmentally friendly, and aligned with climate change mitigation efforts.
- Support and conduct additional research on innovative and sustainable solutions and scale up its adoption.
- Raise awareness and improve knowledge on microbiome as a key player in increasing nutrient availability and plant and soil protection.
- Support the targeted research and innovation and support the wide adoption of soil microbes as real and feasible solutions to partially replace, fully replace, or optimize the use of mineral fertilizers and promote plant growth.
- Foster the use of biofertilizers and biostimulants as complements and alternatives to mineral fertilizers to sustainably increase soil fertility.
- Embrace complexity, and mixed or complex biofertilizers, based on the existing soil microbiome.
- Promote research and better knowledge of the benefits of using biostimulants, especially regarding the wide variety of sources and the advantageous effects of different biostimulants on a variety of crops, soil types, and climatic conditions.
- Improve the knowledge on nutrient content of recycled and reused products and organic wastes to support the circular economy and reduce the agrifood systems' carbon footprint.

Recommendation 3. Assess the quality and safety of all nutrient sources applied to soils to avoid or reduce environmental contamination and health problems.

The following measures are recommended:

- Promote the quality and safety assessment of mineral fertilizers to better understand the heavy metal content and act against environmental pollution.
- Raise awareness and develop national, regional, and global monitoring plans to better understand the origin and the consequences of fertilizer use and heavy metal pollution.
- Promote the evaluation of quality and safety of organic nutrient sources under the International Network of Fertilizer Analysis (INFA) and developing harmonized methods and tools for that purpose.
- Assess and monitor the quality and efficiency of traditional and new sources of nutrients. This is especially relevant in the case of new or recycled sources and nanoparticles to support their implementation on bigger scales.
- Raise awareness on fertilizer quality assessment as the best ally against undesirable effects of nutrient sources on environmental quality, and human and animal health.
- Evaluate the biodegradability of different materials used in agriculture, including plastics, and fertilizer coatings.
- Promote capacity development and improvement in the performance of laboratories for tasting efficiency, quality, and safety.
- Allocate research, resources, and capacity development to emerging problem of plastics and microplastics content in crop soils.

Recommendation 4. Advocate for the adoption of SSM practices since it still represents the most cost-effective solution to increase soil nutrient content

The following measures are recommended:

- Promote the adoption of the Voluntary Guidelines for Sustainable Soil Management and advocate SSM as the most cost-efficient strategy to increase soil macronutrient and micronutrient availability and improve food quantity, quality, and safety.
- Integrate organic sources (such as green manure or residue compost) to improve productivity, nutrient availability and contribute to fertilizer cut down.
- Explore alternatives and synergistic effects to increase soil micronutrient content including the combination of SOM additions and micronutrient fertilization, the optimization of micronutrient availability with macronutrient fertilization, and SSM practices in association with micronutrient applications.
- Advocate for fertilization plans that consider the use of composted organic materials, and the combination of different nutrient sources to optimize soil fertility and soil health.
- Feed crops in addition to soils (paired with plant-based approaches like biofortification).
- Follow the integrated soil fertility management principles and ensure matching nutrient availability with crop demand.
- Combine bio-based fertilizers and inorganic fertilizers to promote yields increase, NUE and reduce GHG emissions.

Recommendation 5. Consider driving forces such as water availability, climate change, poverty and the fertilizer crisis and promote a soils for nutrition agenda.

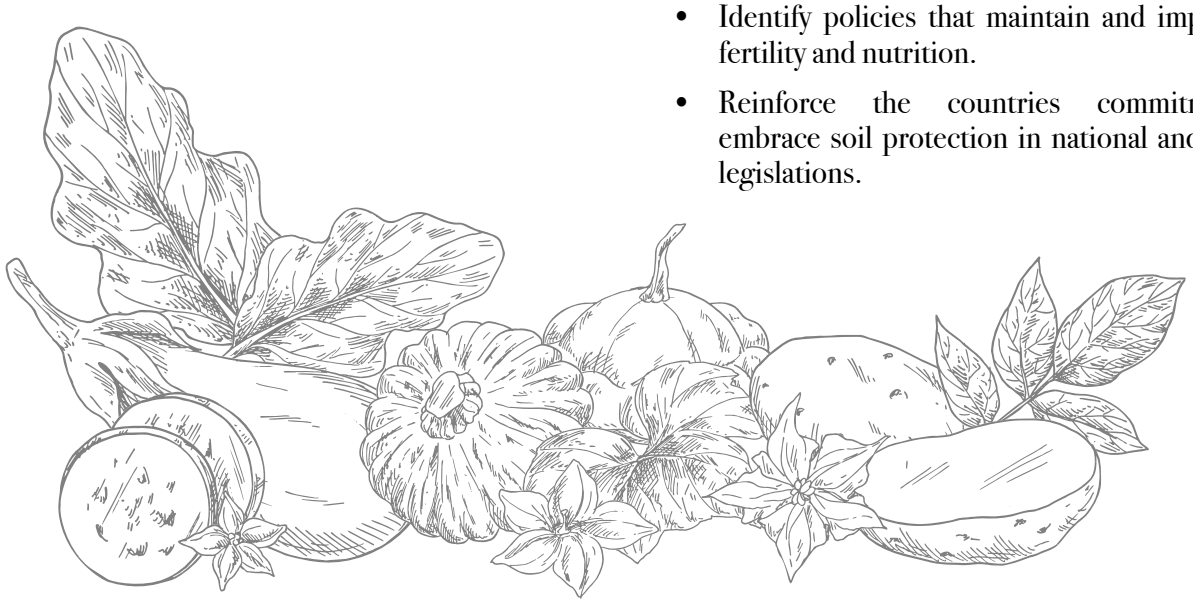
The following measures are recommended:

- Consider water management as a key element in any soil fertility plans since it can be a severe and difficult to overcome barrier for the implementation of SSM practices.
- Work towards increased NUE, taking into account climate change.
- Include integral and inclusive solutions to soil fertility loss that also improves farmers' incomes and support them to cope with the fertilizer crisis.
- Promote the scale up of good practices that have proven to enhance soil fertility and productivity while reducing significantly soil degradation and GHG emissions.
- Enhance farmers' knowledge accessibility by innovative approaches including the Soil Doctors Programme and strengthening the capacities of agrodealers as the first source of technical advice for farmers.
- Launch the International Soil Fertility and Fertilizer Network (INSOILFER) to address nutrient imbalances and promote the adoption of soils for nutrition concept for making soils healthy and fertile by 2030 as a contribution to the transformation of agrifood systems.

Recommendation 6. Advocate for the inclusion of soil fertility and soil health in the legal framework of countries in relation to the One health approach linking human nutrition, environmental and soil health.

The following measures are recommended:

- Identify policies that maintain and improve soil fertility and nutrition.
- Reinforce the countries commitment to embrace soil protection in national and regional legislations.



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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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