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FORUM

Sustainability Nexus AID: soil health

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Abstract
The Sustainability Nexus Analytics, Informatics, and Data (AID) Programme of the United Nations University (UNU), aims to provide information, data, computational, and analytical tools to support the sustainable management and long-term security of natural resources using a nexus approach. This paper introduces the Soil Health Module of the Sustainability Nexus AID Programme. Healthy soil is crucial for life on Earth, and it is essential for ecosystem services and functioning, access to clean water, socioeconomic structure, biodiversity, and food security for the growing population of the world. Healthy soils contribute to mitigating the effects of climate change and reduce the consequences of extreme events such as flooding and drought. Healthy soils influence the hydrologic cycle by regulating transpiration, water infiltration, and soil water evaporation affecting land–atmosphere interactions. The Soil Health Module of the UNU Sustainability Nexus AID Programme aims to evolve into the ultimate focal point, supporting a diverse array of stakeholders with state-of-the-art data and tools that are essential for soil health monitoring and projection. This paper discusses the importance of adopting a nexus approach for ensuring soil health, explores the AID tools currently at our disposal for quantifying and predicting soil health, and concludes with recommendations for future effort and direction within the Sustainability Nexus AID Programme concerning soil health.

Keywords Analytics · Informatics · Data · Soil health · Sustainable development · Global environmental change · Soil security

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1 Why Soil Health matters

Healthy soil supports life on earth through maintaining ecosystems that provide food, feed, and fibre whilst supporting earth system functions such as waste recycling, climate, flood, and water regulation. Soil health can be defined as, 'the continued capacity of soils to support ecosystem services' (EU Commission 2020). Neglecting proper soil care and ineffective management practices have often resulted in significant challenges such as lower agricultural productivity, food insecurity, soil degradation, and economic instability. Historical evidence underscores the profound socio-economic consequences of neglecting soil as a natural resource. Notable examples include the Dust Bowl in the USA in the 1930's, which led to mass migration to the Western US, and the demise of ancient civilizations in the Middle East (Butzer 2012) due to soil deterioration caused by soil salinization (Shokri et al. 2024). Healthy soils contribute to a range of ecosystem services (Robinson et al. 2014; Smith et al. 2015), which are fundamental to achieving the United Nations Sustainable Development Goals (SDGs) (Keesstra et al. 2016). A recent analysis showed that healthy soils contribute to almost all of the UN SDGs (Smith et al. 2021). Healthy soils are essential to regulate climate (SDG 13: Climate Action), maintain biodiversity (SDG 15: Life on Land), and ensure food security (SDG 2: Zero Hunger). As indicated by the Food and Agriculture Organization of the United Nations (FAO), healthy soil is "a prerequisite to achieve the SDGs" (Fig. 1).

In 2015, more than 200 scientists from 60 countries compiled the first United Nations World Soil Resource Report (FAO and ITPS 2015). Although there is cause for optimism in some regions of the world, the report stated that "the majority of the world's soil resources are in only fair, poor or very poor condition." Soil erosion, loss of soil organic carbon, and nutrient imbalance are highlighted as the most significant threats to soil function globally, and to soil's contribution to the delivery of ecosystem services. The 2015 FAO and ITPS report outlined four priority actions to stabilize or reverse over-exploitation of global soil resources:

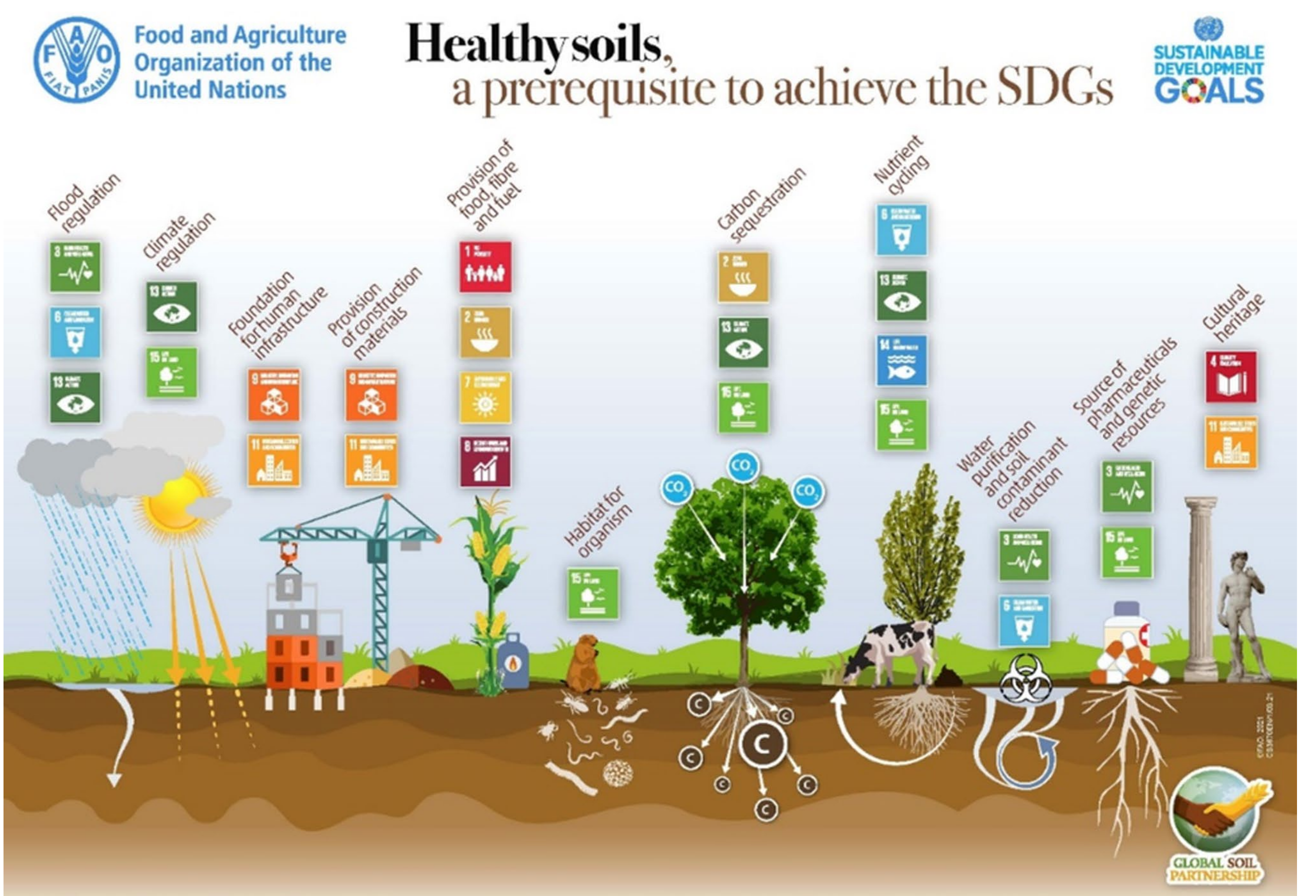

Fig. 1 Healthy soils are essential to achieve UN SDGs (after FAO 2021)

1. Minimise further degradation of soils and restore the productivity of soils that are already degraded in those regions where people are most vulnerable.
2. Stabilise and increase the global stores of soil organic matter (i.e. soil organic carbon (SOC) and soil organisms).
3. Stabilise or reduce global N and P fertilizer use while simultaneously increasing fertilizer use in regions of nutrient deficiency.
4. Develop monitoring systems to determine the current state and trend of soil health.

Since the publication of the report, there have been notable efforts in Europe where the Mission on Soil Health and Food was launched in 2021. This ten-year program focuses on research and activities aimed at addressing soil degradation and restoring soil health across Europe.

2 The need for a nexus approach

Beyond the critical role of soil in food security and essential ecosystem functions, soil health is integral to the well-being of humans, animals, plants, and the environment. Soil health is inherently interconnected with a range of factors, including ecosystem services, agricultural practices, water management, and climate regulation. The science of soil health encompasses multiple disciplines, linking agriculture, soil science, policy, environmental health, engineering and sensing technology, economics, and social sciences. By integrating these interconnected disciplines and dimensions, a nexus approach offers a comprehensive framework for understanding and managing soil health. Population growth and climate change have placed ever-increasing stress on interconnected resources (e.g., food, water, energy, and nutrients) and competition for these resources among different sectors. A Nexus approach provides an opportunity to comprehensively understand and systematically analyze the complex interrelationships among the different resources, human activities, and climate, and to manage these interactions to improve soil health sustainably. This approach recognizes that soil dynamically interacts with other environmental and socio-economic systems. For example, soil health is both influenced by and influences water availability and quality, which in turn affects agricultural productivity and ecosystem stability. Additionally, soil plays a critical role in carbon sequestration and climate regulation, thus influencing and being influenced by climate change. Implementing a nexus approach involves coordinating across multiple sectors and disciplines to ensure that soil management practices are mutually reinforcing rather than conflicting. This coordination helps in developing integrated policies that address soil degradation while also enhancing water conservation, improving agricultural practices, and mitigating climate change impacts. Such an approach promotes sustainable soil management by considering the cumulative effects of various interventions and optimizing the use of resources. Furthermore, a nexus approach facilitates the development of innovative solutions that can address multiple objectives simultaneously, such as increasing agricultural productivity while improving soil health and conserving water. This will allow better coordination of use and management of limited natural resources sustainably across scales and sectors, identifying trade-offs and synergies, and more effective and integrated decision-making, implementation, and evaluation. Moreover, a Nexus approach encourages a broader range of stakeholder involvement, thus increasing the likelihood of achieving food security, environmental health, and sustainable development goals.

Recognizing the importance of soil health, the Mission Board's proposal for Soil Health and Food to the European Commission in 2020 sets several objectives to improve soil health and preservation (European Commission 2020). Those objectives include reducing land degradation; conserving and increasing soil organic carbon stocks; achieving no net soil sealing and enhancing the reuse of urban soils for urban development; reducing soil pollution and promoting restoration; preventing erosion and improving soil structure; reducing the EU's global footprint on soils; and increasing soil literacy among students, land managers, advisors, and consumers. These goals highlight the multidisciplinary nature of soil health and underscore the necessity of a nexus approach to effectively address soil health challenges (Lehmann et al. 2020). The Resource Nexus approach (Brouwer et al. 2023) could help achieve the SDGs by promoting sustainable resource management that maintains soil health. This holistic strategy enhances food security (SDG 2), supports climate resilience (SDG 13), and fosters economic growth (SDG 8) while protecting ecosystems and life on land (SDG 15). By prioritizing practices that sustain soil health and fertility and reduce environmental impact, the nexus approach could ensure long-term environmental sustainability.

3 The aid of the AID

Significant breakthroughs in exploring big data, pattern recognition, and predicting complex behavior and trends have been made through Industry 4.0, and environmental science in general, and soil health in particular, are no exception. The integration of digital technologies and novel algorithms and methodology can play a significant role in ensuring soil health and security. Analytics, informatics, and data (AID) play a crucial role in facilitating integrated soil health management by enabling quantitative and data-driven decisions.

Through advanced data collection methods, such as remote sensing and IoT-enabled soil sensors, comprehensive datasets on soil moisture, nutrient levels, and microbial activity can be gathered in real-time. These datasets, when analyzed using sophisticated informatics tools, provide insights into soil conditions, revealing trends and patterns that inform best practices in agriculture. For example, data and analytics can be used to forecast extreme land surface temperature affecting soil health and plant growth (Aminzadeh et al. 2023) or examine soil degradation risks (Prăvălie et al. 2024) and devise interventions, when necessary, while geographic information systems (GIS) can map soil health across large areas, allowing for targeted management and remediation strategies. There are several successful examples and flagship projects utilizing AID tools to monitor and manage soil health including EU-funded AI4SoilHealth project,[1] the LUCAS topsoil database[2] and GSOCmap (Global Soil Organic Carbon Map), which uses data from soil samples, remote sensing, and other sources to create a global map of soil organic carbon.[3]

The new generation of AID tools could significantly contribute to precision agriculture, environmental protection, and the long-term security of natural resources by utilizing sensors and data analytics to monitor and manage soil conditions in real time. Data-driven decision-making is possible through advanced analytics and machine learning algorithms that can be used to characterize various aspects of soil health, crop production, soil salinization, soil composition, and other soil-related processes (Borrelli et al. 2017; Hengl et al. 2017; Hassani et al. 2020, 2021, 2024). This could empower policymakers, business owners, farmers, and researchers to make informed decisions regarding sustainable and effective soil management and strategies, leading to improved crop yields and sustainable development.

4 Sustainability Nexus AID programme: soil health

The Sustainability Nexus AID Programme, launched by the United Nations University (UNU), focuses on promoting the Nexus approach to integrated resource management for sustainable development and fulfilling the UN 2030 Agenda. This Programme focuses on identifying, developing, and promoting data, information, computational techniques, and analytical tools that facilitate sustainable management of water, soil, waste, energy, and geo-resources based on nexus thinking. The AID Programme incorporates various modules to address various problems related to sustainable development including Air Pollution, Biological Invasions (Robeck et al. 2024), Drought (Huning et al. 2024), Flood, Food Security, Greenhouse Gas Emission, Groundwater, Infrastructure Resilience (Erfani et al. 2024), Landslides and Land Subsidence (Motagh et al. 2024), Land Use Land Cover Change, Sea Level Rise, Soil Health, Storms (Papalexiou et al. 2024), Wetlands, and Wildfire, with the potential to incorporate new modules in the future. The AID program benefits from the expertise of an international and diverse network of scientists and professionals working at the forefront of global efforts to address planetary challenges related to climate, nature, and pollution, thus contributing to the achievement of the 2030 UN Sustainable Development Goals (SDGs).

The Soil Health Module was established with the vision of becoming a focal destination for resources, providing a wide range of products to a diverse range of stakeholders through a comprehensive list of AID tools crucial for soil health monitoring and projection. One of the key goals is to effectively bridge the gap between science and policy in addition to focusing on capacity building and to provide a collaborative platform where different stakeholders can share their insights, findings, and best sustainable practices for soil management. The Soil Health Module includes scientists specializing in various aspects of soil health, dedicated to offering the necessary expertise for sustainable soil health management. This module discusses some key platforms such as the FAO Soil Portal, International Soil Reference & Information Centre (ISRIC), FLUXNET, USDA Web Soil Survey (WSS), 3D Soil Hydraulic Database of Europe, European Soil Data Centre (ESDAC), and UKCEH Countryside Survey. These platforms offer crucial data relevant to soil health, forming the foundation of our future activities. As the module evolves, we anticipate expanding this list of datasets and tools. Additionally, we aim to incorporate other major initiatives with a shared interest in soil health, identifying gaps in data, tools, and computational power, fostering capacity building and stakeholder engagement, and developing policy briefs for the relevant organizations. Furthermore, we plan to offer and promote open access training and educational materials on various aspects of soil health tailored for a wide array of stakeholders.

5 Soil health AID tools

Various analytical methods, measurement tools, and data analysis techniques are used to actively monitor and evaluate soil health conditions. State-of-the-art technologies, including sensor networks, remote sensing devices, and automated data collection systems are harnessed to deliver precise and

[1] https://ai4soilhealth.eu/

[2] https://esdac.jrc.ec.europa.eu/projects/lucas

[3] https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-soil-organic-carbon-map-gsocmap/en/

comprehensive assessments of soil conditions. By combining AI-based methods with data from traditional soil sample analysis and digital soil mapping technologies, one could capture not only fundamental soil metrics such as nutrient levels but also facilitate the analysis of complex datasets obtained from diverse field campaigns at different spatio-temporal scales, thus enabling a more nuanced understanding of soil health dynamics.

At the global scale, the Harmonized World Soil Database (HWSD), resulting from collaboration of the FAO and other organizations such as the ISRIC-World Soil Information and Joint Research Centre (JRC) of the European Commission includes over 15,000 different soil mapping units. The dataset integrates global soil information from existing regional and national updates with data from the FAO-UNESCO Soil Map of the World. Additionally, for more than 50 years, ISRIC-World Soil Information has compiled and harmonized data on soils and their properties.

At the continental scale, the European Soil Data Center (ESDAC) is the focal point for soil data, support to policy making, and awareness raising for the European Union (EU) (Panagos et al. 2022). ESDAC is an integral part of the EU Soil Observatory (EUSO) and aims to have an even stronger role in supporting the EU and regional policies. ESDAC encompasses data on soil physical and chemical properties (e.g. pH, texture, NPK), soil functions (e.g., water retention, saturated hydraulic conductivity, soil biomass productivity), soil threats (e.g., soil erosion, soil organic carbon decline, soil biodiversity loss, diffuse pollution, landslides and soil nutrients) and global datasets (e.g. global soil erosion, soil organic carbon and soil biodiversity threat). In addition, ESDAC hosts more than 6,000 maps, 8 atlases, hundreds of documents, and more than 500 publications from JRC's soil-related projects, including LUCAS campaigns. The LUCAS topsoil database is the result of the LUCAS Soil Module, including data for physical, chemical, and biological properties for 4 soil surveys in the EU (2009/12, 2015, 2018, and 2022). The 3D Soil Hydraulic Database of Europe further provides soil hydrophysical characteristics including soil moisture dynamics and hydraulic conductivity in Europe.

At the national level, various inventories such as those from the United States Department of Agriculture (USDA), the UK Centre for Ecology and Hydrology (UKCEH) Countryside Survey, the National Bureau of Soil Survey and Land Use Planning (NBSSLUP) of India, and the Federal Institute for Geosciences and Natural Resources (BGR) in Germany serve as valuable sources of information on soil health condition (see further details and specifications of AID tools at https://www.sustainabilityaid.net/soilhealth).

In addition to these tools and datasets focusing on soil functioning and characteristics, the worldwide FLUXNET network has extensively monitored the exchange of trace gases, energy, and water vapor between the land and atmosphere. This network provides invaluable data that enhances our understanding of the intricate relationships between soil and climate within the broader context of land–atmosphere interactions. Moreover, the LANDSUPPOR spatial decision support platform (https://www.landsupport.eu/) comprises 15 macro-tools and more than 100 elementary tools designed to support analysis and decision-making across a broad spectrum of subjects, which require a nexus approach. Its web-based geospatial cyberinfrastructure integrates soil and other environmental data, along with modelling engines, to provide its free services.

The aforementioned tools listed on the webpage of the Soil Health Module of the AID programme could be extended in the future to include additional tools useful to investigate and quantify soil health at different spatial and temporal resolutions under a wide range of boundary conditions. All the tools and datasets presented in this manuscript are open access and publicly available. They can be utilized for a variety of purposes, such as research and educational activities, depending on the specific needs of the users.

While the initial tools that used soil information often targeted one specific property, such as potential productivity or soil erosion resistance, the new generation of tools can provide real-time or nearly real-time estimates of site-specific conditions (Herrick 2016). Tools applicable across different scales, from precision agriculture to global models, are being developed to identify soil conditions and potentials aiming to integrate soil health criteria into scientific assessments, land use planning, and management.

6 The way forward

Achieving sustainable soil management necessitates a nexus approach that integrates natural, social, and economic sciences with input from a diverse range of stakeholders, including farmers, consumers, industry representatives, and policymakers. The Soil Health Module of the UNU Sustainability Nexus Programme aims to become a key component in advancing integrated soil management by addressing critical gaps in data, tools, and stakeholder engagement. Recognizing the integral role of soil health in environmental sustainability, agricultural productivity, and climate resilience, future efforts will focus on several strategic areas. A primary objective is to identify the module's datasets and analytical tools. This will involve the incorporation of emerging data sources, such as advanced remote sensing technologies and comprehensive soil microbiome studies. By addressing current data deficiencies and improving the spatial and temporal resolution of soil health assessments, particularly in underrepresented and data-poor regions, the module seeks to provide a more detailed and actionable understanding of soil conditions. This expanded dataset will support more accurate and regionally relevant soil management practices.

Effective scientific progress hinges on robust collaboration within the community. The Soil Health Module of the AID Programme outlines several tools and opportunities to enhance soil health and community well-being. However, technical challenges inherent in many of these methods, often a limiting factor in their application is the touch point of the in-between spaces. Bringing together experts of different backgrounds (e.g. pedologists,biogeochemists, physical chemists, and engineers) requires rethinking our collaborative approaches in large projects. It's no longer sufficient to carve off individual puzzle pieces at the start of a project and assemble them on the back end at the conclusion. Sustainable, productive, and organic collaborations call for ongoing and open communication throughout the project's duration. This communication must extend beyond the scientific community to also include local stakeholders. Moreover, collaboration must extend beyond the traditional research outputs like papers and policy guidance documents to include new digital assets such as vocabularies, ontologies, and other semantic standards. A major obstacle in the current data-to-decision ecosystem is the integration of diverse data streams and models. Since each dataset or model is developed for specific purposes, extending their utility requires a shared technical language that is widely adopted across the stakeholder community. The soil health stakeholders and the scientific community can benefit from the experiences of the free and open-source software community and collectivization movements to co-develop and co-govern these resources effectively.

The Soil Health Module acknowledges the value of collaboration and is open to involving other major initiatives and institutions focused on soil health. This collaborative approach aims to integrate resources, expertise, and data to create a more impactful and cohesive effort. The module is also committed to identifying and addressing gaps in existing data, tools, and computational capacity to advance soil health knowledge. Capacity building and stakeholder engagement are central to this strategy, including the development of open-access training materials and educational resources. Disseminating novel insights related to soil health through policy briefs and review articles is another plan within the Soil Health Module to ensure informing decision-makers and the broader scientific community. At a later stage, such efforts could contribute to formulating a potential proposal that could serve as the foundation for the "UN Soil Health Law and Monitoring," thereby contributing to global efforts in sustainable land management and achieving the UN SDGs goals. Through this multifaceted approach, the members of the Soil Health Module aim to make significant contributions to understanding, promoting, and preserving soil health on a global scale.

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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