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SOILS FOR EUROPE
Footprint on soils

Scoping document

Outlook on the knowledge gaps the EU global footprint on soils

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Outlook on the knowledge gaps the EU global footprint on soils

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Introduction

This Think Tank (TT) focuses on Specific Objective 7 (SO7) of the European 'EU Soil Mission: A Soil Deal for Europe' (hereafter Soil Mission), that relates to reducing the EU global footprint on soils. Within this specific Soil Mission objective, two main targets are defined in the Soil Mission Implementation Plan:

- T 7.1: Establish the EU's global soil footprint in line with international standards
- T7.2: The impact of EU's food, timber and biomass imports on land degradation elsewhere is significantly reduced without creating trade-offs

These objectives have to be in line with the Zero Pollution Action Plan. This implies that air, water and soil pollution will have to be reduced to levels no longer considered

harmful to health and natural ecosystems, that respect the boundaries with which our planet can cope, thereby creating a toxic-free environment, by 2050. The main objective of this document is to highlight actionable knowledge gaps and research themes, that are critical to achieve to attain the SO7 specific objectives.

Background to the international dimension (as presented in the Soil Mission Implementation Plan)

SO7 adds an international dimension to the EU Soil Mission, which is, in its other objectives, primarily focused on improving soil health and soil functioning in the European Union. As stated in the Mission Implementation Plan, soil health is crucial for three UN conventions (UNCBD, UNCCD, UNFCCC), as well as for the Sustainable Development Goals (SDGs), and is an issue of worldwide concern. To avoid negative impacts of EU actions on soils outside the EU (mostly in terms of consumer demands), the Soil Mission acknowledges the need for global alignment of the soil health concept and actions to reduce the soil footprint outside the EU from imports of food, biomass, and timber. This focus on biomass has been questioned by multiple stakeholders, as highlighted in the initial knowledge gaps. The Soil Mission Implementation Plan emphasizes that the beyond-EU dimension can and should leverage existing partnerships.

For Africa, the Food and Nutrition Security and Sustainable Agriculture (FNSSA) partnership, part of the African Union-European Union High-Level Policy Dialogue (HLPD), is indicated as a potential starting point. It focuses on soil health for sustainable food systems. The related Horizon 2020 projects Soils4Africa and LEAP4FNSSA have invested first efforts to improve the quality and availability of African soil data, to develop field survey protocols, and to coordinate and support research and innovation on sustainable agriculture. For the non-EU countries around the Mediterranean, the PRIMA Research and Innovation Programme addresses water and agri-food systems in the Mediterranean, in order to prevent further degradation and restore damaged lands in the Southern Mediterranean. It has funded a number of projects related to soil management.

In Latin America and the Caribbean, cooperation is primarily aimed to be focused under the EUCELAC Foundation, that emphasizes sustainable agriculture and bioeconomy research in line with the EU's Horizon Europe program. Japan and Canada are also key partners. Japan seeks to align its Moonshot program with the EU's Soil Mission, while Canada contributes to designing living labs and R&I collaboration. The Soil Mission also aims to support collaboration with the FAO, particularly its Global Soil Partnership, that aims for a harmonized framework for soil data and contributes to the FAO's Global Soil Biodiversity Observatory and initiatives on soil biodiversity conservation. Finally, the Implementation Plan states that Member States' involvement in the 4per1000 initiative, launched at COP 21, establish an International Research Consortium (IRC) on soil and carbon to enhance global R&I cooperation. This will be guided by the activities of the ORCaSa Horizon Europe project (“Operationalizing International Research Cooperation on Soil Carbon”), and the Global Research Alliance on Agricultural Greenhouse Gases.

Importance

The issue of soil degradation is a major concern in the Global South, affecting millions of individuals who depend on agriculture for their livelihoods. According to FAO, one-third of global agricultural land is experiencing human-caused degradation, and the rate at which this is happening is accelerating due to population growth. The areas that are most affected by soil erosion and fertility loss are those that experience the greatest decrease in yields due to climate extremes, the fastest increase in aridity, and have the highest risk for food security. Stopping soil degradation is therefore essential to achieve the goal of zero hunger. The majority of the 1.3 to 3.2 billion people affected by this issue live in poverty in developing countries. The role of the EU in this global problem cannot be neglected (European Environment Agency (EEA) et al. 2020), especially in terms of biogeochemical flows (nitrogen and phosphorus cycles), biomass flows, soil health and land system change; this is crucial to avoid an ecological poverty trap, where soil degradation could erode potential for eradicating poverty (Wackernagel et al. 2021).

State of the Art

The broader state-of-the-art regarding Soil Mission Objective 7 is challenging to assess. As highlighted multiple times during the ongoing development of this outlook document, no existing study has comprehensively quantified the detailed impact of EU activities on global soil health and functions. Furthermore, there is no clear consensus on which soil functions and ecosystem services should be prioritized, or how such a footprint can be achieved.

The Soil Mission recognizes that even at the EU level, assessing the overall status of soil health remains a significant challenge. At the EU level, the combined LUCAS soil survey, soil module and soil methodology provide harmonized and statistically relevant data and protocols on the monitoring and status of key aspects of soil health (European Commission: Joint Research Centre et al. 2021). Yet, unlike other resources such as water, there is currently no legal requirement for EU member states to report on soils in a harmonized and standardized manner, although discussions on the Soil Monitoring Law are continuing. This leads to inconsistent levels of soil monitoring across the EU. Additionally, the EU soil survey faces the challenge of adapting to the evolving policy needs of both national and EU policymakers. A significant difficulty is the specific quantification of the human activity footprint in the LUCAS dataset. This is testimony to the formidable task that is ahead for achieving Soil Mission objective 7, which lumps all EU-based Soil Mission objectives into one single objective for soils outside the EU, along with all related harmonization and integration issues, into one worldwide perspective.

Although overarching efforts to quantify the EU impact on soils outside the EU are absent, this definitely does not imply there are no current research studies that have tried to assess the impact of EU policy and actions on soils outside of the EU. We bring together here a summary of recent efforts. We also identify key databases that offer the potential for assessing EU global soil footprint. It should be emphasized that none of the referred

papers includes a comprehensive impact assessment on soil functioning and health, specifically. We emphasize that this document focuses on the footprint of food, fiber and biomass production, as these are the specific focus of SO7. This does not imply that no other footprints are worthwhile to investigate, as is also highlighted by multiple members of our Think Tank. As explained further in the document, expanding the Mission objective to encompass a broader definition that allows for a comprehensive assessment of impacts is worthwhile to consider in this regard. This revision would enable future policy actions to address not only biomass and food-related soil impacts but also non-biomass related influences such as pesticides, mining activities, infrastructure developments (e.g., for tourism), and climate change effects. It may also be beneficial to consider the impact of exported soil amendments (e.g., herbicides, pesticides) and waste (resulting e.g. in landfills) from the EU on soils outside the European Union.

How to establish global ecological footprint of the EU-food and biomass system

The ecological footprint (EF) of the EU-27 between 2004 and 2014, and how it exceeded regional bio-capacity, was assessed by Galli et al. (2023). The study used an extended multi-regional input–output approach (MRIO), highlighting food as a major contributor. The MRIO approach can analyse the ecological footprint (EF) and, as part of the EF, the food footprint (FF) of a region (e.g. a country, a group of countries), considering both the demand and supply aspects, including trade and multiple externalities. However, it needs to be stressed that the EF was focused on resource dependence and carbon emissions, rather than soil impact. The overall conclusion was that a quarter of the EU bio-capacity for food consumption originates from non-EU countries (According to the Global Footprint Network, biocapacity stands for the regenerative capacity of our planet's ecosystems. The biocapacity metric, therefore, quantifies the renewal rate of ecosystems around the globe). Vanham et al. (2023) performed a similar approach, to track the land footprint (LF) and water footprint (WF) of food consumption in the EU. The EU LF and WF were estimated at 140-222 Mha yr^{-1} and 569-918 km^3 yr^{-1}, constituting 5-7% of global agricultural LF and 6-10% of global agricultural WF. Most of this footprint (>50%) was within the EU in all model variations. While the impact at EU level was similar in the different model variations, the non-European impact differed quite strongly according to impact region across the world, between different model runs. The study underlines the importance of a consistent and standardised methodology, since numbers differed strongly from similar earlier efforts, and were highly variable also within the study. Also here, no direct impact on soil functions was considered, but the LF clearly shows the large potential soil surface affected. It is clear that the metric used is simplified (e.g. it does not account for how land and water are managed, or when the land use was changed to agriculture) and thus contains potential inherent limitations and biases, e.g. preferring intensive land management over extensive management.

Giljum et al. (2016) identified priority areas for European resource policies using an adapted MRIO-based footprint assessment, presenting a comprehensive assessment for the EU from 1995 to 2011. The study revealed a significant shift in the origin of raw materials, with the share extracted within the EU falling from 68% in 1995 to 35% in 2011. Materials extracted in China equaled the share of EU's own material extraction by 2011.

Regarding product composition, construction was confirmed as the most important sector contributing to the material footprint, followed by the group of manufacturing products based on biomass. The study highlights the fact that studies applying economy-wide material flow analysis so far mostly produced aggregated national indicators, making the results difficult to connect to policies, which are often designed for single sectors or consumption areas. No specific soil impact could be assessed from this study.

Bruckner et al. (2019) performed a global cropland footprint of the EU's non-food bio-economy. They linked the biophysical model LANDFLOW with the EXIOBASE 3 MRIO model, to provide detailed insights into product and country-specific footprint. The study revealed that two-thirds of the cropland required for the EU's non-food biomass consumption is located outside the EU, particularly in China, the US, and Indonesia, Notably, oilseeds for biofuels, detergents, and polymers represent the dominant share (39%) of the EU's non-food cropland demand. This paper provided the first assessment of the global cropland footprint of non-food products of the European Union (EU). The study concluded that if the EU Bioeconomy Strategy is to support global sustainable development, a detailed monitoring of land use displacement and spillover effects is decisive for targeted and effective EU policy making. The paper points to the fact 'that Europe stands out as the only world region that is a net-importer of the four major natural resource categories: materials, water, carbon and land'. No specific soil health effects were investigated in the paper.

MRIO?

The Multi-Regional Input-Output (MRIO) approach is an analytical technique used in economics to explore the relationships between different regions or countries within the global economy. It focuses on:

Economic interactions: MRIO models capture how industries in different regions or countries interact with each other. They account for the flow of goods and services across regional boundaries, offering a detailed view of economic dependencies and supply chain linkages.

Environmental and social Impacts: by integrating economic data with environmental and social data, MRIO models can assess the indirect effects of production and consumption activities. This includes tracing the environmental impacts, such as carbon emissions or resource usage, and social effects, like employment, associated with production processes throughout global supply chains.

Sectoral and regional Analysis: MRIO models divide the economy into sectors and regions, providing insights into the economic activities within each sector and the transactions between sectors across different regions.

https://www.footprintnetwork.org/resources/mrio/

Key papers on country-specific assessment

- Cederberg et al. (2019) focused on the environmental impacts of Swedish food consumption, specifically in relation to agrochemicals, greenhouse gas emissions and land impacts. Equally utilizing the EXIOBASE database, the research calculated novel footprint indicators for pesticides and antimicrobial veterinary medicines. Key findings revealed that a significant share of Sweden's pesticide footprint is embedded in imports, primarily from Europe and Latin America. The paper specifically points to the 'need for better data and statistics on the use of pesticides, veterinary medicines and agrochemicals residuals (especially in developing countries) as well as improved spatial data on agricultural activity to further reduce uncertainty in the environmental footprint of Swedish food consumption.'
- Kalt et al. (2021) performed an analysis tracing Austria's biomass consumption to source countries, using a physical consumption-based accounting approach, combined with national statistics and process chain modelling. 55% of Austria's total biomass consumption originated from domestic forestry or agriculture, and 30% from neighbouring countries. Products with the largest biomass footprints like beef, pork, milk, cereal products, paper, and wood fuels were primarily sourced from Central Europe. Biomass from non-EU countries accounted for about 8% of Austria's primary biomass footprint. This paper indicates the strong dependence of country- or region-specific preferences for the EU global footprint, which thus likely also accounts for the soil footprint. More specifically, the paper highlights that 'in Austria, strong preference for food and bioenergy from domestic sources is prevalent, while especially biomass imports for energy are met with scepticism.

Habitat loss and agricultural trade

Schwarzmueller and Kastner (2022) performed a study that linked agricultural trade to global loss of species. Utilizing FAOSTAT data and the Species Habitat Index (SHI) as a measure of ecosystem intactness, the research covered trade flows between 223 countries over 15 years. It showed agricultural expansion as a major driver of biodiversity loss, especially in South America, Southeast Asia, and Sub-Saharan Africa, also showing that Western Europe, North America, and the Middle East have significant biodiversity footprints outside their borders. Particular attention was paid to soybeans, palm oil, and cocoa. The authors also indicate the limitations of their study: "directly relating the species habitat loss to the production of agricultural products, we neglected the role of other drivers like logging or mining. Although agricultural expansion is by far the most widespread form of land-cover change, this introduces some uncertainty when these products are traded between different countries."

In another study linking biodiversity decline to agricultural expansion, Zabel et al. (2019) predicted global impacts of future cropland expansion and intensification on biodiversity. Although, like all others, this study was not aimed at assessing soil effects, it points to the interesting observation that 'production gains will occur at the costs of biodiversity

predominantly in developing tropical regions, while Europe and North America benefit from lower world market prices without putting their own biodiversity at risk. Cropland expansion mostly affects biodiversity hotspots in Central and South America, while cropland intensification threatens biodiversity especially in Sub-Saharan Africa, India and China.' This points to the importance of prioritization to balance biomass transfers with conservation goals, preferentially first tackling the most affected regions.

Analyses and Tools from the JRC

The Joint Research Centre (JRC), in collaboration with Eurostat, has developed a model to estimate the European Union's (EU) land footprint—the total area required to produce the goods consumed by its population. This model evaluates three land types: cropland, grassland, and forest land used for timber products. It accounts for both domestic land use within the EU and international land used for imported products. Over 500 food and bio-based products were individually analyzed to accurately attribute the origin of agricultural or forest land utilized in production. For instance, the cropland associated with EU imports of chocolate from Switzerland is traced back to the countries where the cocoa was originally cultivated (De Laurentiis et al. 2024, Sala et al. 2025).

Between 2014 and 2021, the EU consistently remained a net importer of cropland—land used to grow products consumed within the EU—and a net exporter of grassland, which supports products consumed outside the EU. The net trade balance for forest land varied annually, with imports and exports fluctuating within a similar range. In 2021, the EU imported approximately 50 million hectares of cropland, an area comparable to the size of Spain, while exporting about 28 million hectares. Domestically, the EU utilized 94 million hectares of cropland, measured in terms of harvested area. The primary countries supplying cropland to the EU were Argentina, Brazil, and Ukraine, with key imports including vegetable oils (such as palm and sunflower seed oil), oilseed crops (like rapeseed and soybeans), and food industry residues like oilcakes, predominantly used as animal feed.

In 2021, the average EU citizen utilized 0.26 hectares of cropland to meet their annual consumption needs for food and other bio-based products, including livestock, oils, and cotton. In contrast, the global average was approximately 0.19 hectares per person. Notably, the EU's per capita cropland use slightly exceeded the 0.25-hectare threshold per global citizen established by the Planetary Boundaries framework, a limit set to prevent irreversible environmental damage.

Overarching conclusion

The state-of-the-art analysis shows that the MRIO and the JRC approach can be good starting points for analysing and quantifying the food, feed and timber exchange between the EU and third countries, and its land footprint. A key challenge will lie in relating these mostly land cover-based assessments of footprint to soil health and soil functioning. A

good starting point here will be to rely on databases for soil properties, for which potential examples currently available are summarized below:

- www.isric.org: ISRIC is an independent foundation with a mission to serve the international community as a custodian of global soil information. It supports soil data, information and knowledge provisioning at global, national and sub-national levels for application into sustainable management of soil and land. The ISRIC library has built up a collection of around 10,000 (digitized) maps and 17,000 reports and books. ISRIC highlights standardization as a major challenge, indicating that harmonizing data from diverse sources with varying standards remains complex, affecting the consistency of global soil information. The database is also less fitting to assessing dynamic soil status: soil properties can change over time due to factors like land use and climate change, necessitating continuous updates to maintain data accuracy.
- https://www.fao.org/global-soil-partnership/regional-partnerships/en/: The Global Soil Partnership (GSP), established by the Food and Agriculture Organization (FAO), has formed Regional Soil Partnerships (RSPs) to address specific regional soil challenges and priorities. These RSPs collaborate closely with FAO Regional Offices. The RSPs link up different national soil entities (soil survey institutions, soil management institutions, soil research institutions and soil scientists working in land resources, climate change and biodiversity institutions/programmes), and could be a good starting point for local data for soil functioning assessment.
- https://www.footprintnetwork.org/resources/mrio/: The Global Footprint Network leverages MRIO modelling as a tool for analyzing financial flows between the major economic sectors of different countries. By integrating data from the National Footprint and Biocapacity Accounts, this approach extends to estimating resource flows, allowing for the tracking of resource movement through global supply chains. This provides valuable insights into the ecological impacts of consumption and production patterns. However, the MRIO framework operates at the country or regional level and lacks the granularity to link activities to specific soils or directly assess soil impacts.

Based on the state-of-the-art, it becomes clear why the Mission Objective 7's first sub-objective is focused on setting a clear baseline for establishing the EU's global soil footprint in line with international standards. Current state-of-the-art has not even started performing this exercise at large scale for soil functions and soil ecosystem services, rather linking trade exchanges at best to land use but not to specific ecosystem soil functions and related soil services. As emphasized by van der Putten et al. (2023), soil health laws should account for global soil connections. Establishing these connections will thus be crucial to defining future actions to improve EU soil footprint.

Knowledge Gaps

This section outlines the initial knowledge gaps (KG) as summarized from the broad state-of-the-art before the first review round in 2024. These gaps were first identified

during preparatory meetings held prior to the Barcelona SOLO stakeholder meeting in Autumn 2023 and were further refined through discussions with the stakeholder group in Barcelona and beyond during stakeholder interaction moments. These form the basis for the five detailed priority knowledge gaps outlined further in this document. The specific state-of-the-art is mainly detailed in the priority knowledge gaps to avoid repetition and to allow for a more actionable focus on the priority knowledge gaps.

KG1: Disentangling biomass import effects from other soil impacts

As it is currently defined, the Soil Mission does not account for land degradation resulting from industrial soil contamination, such as that caused by European factories or other polluting economic activities outside EU. Similarly, degradation from open mining activities, which are a source for imported mineral resources, is also excluded. Additionally, the impact of exporting fertilizers and pesticides from the EU, and their subsequent application to soil, may not be adequately considered.

In the Implementation Plan, it is indicated that “a first baseline has to be created by Mission activities, with specific focus on food, feed and fibre imports leading to land degradation and deforestation.” A key point raised by multiple members of the Think Tank, is that the focus on biomass imports is too narrow to allow a baseline for global footprint on soils of EU actions to be formulated.

However, this does not mean that quantifying the impact of imported biomass alone would not be a valuable goal. As highlighted in the state-of-the-art, the potential land impact of the food footprint is already significant (Vanham et al. 2023).

A potential path forward has been suggested by multiple stakeholders: expanding the Mission objective to encompass a broader definition that allows for a comprehensive assessment of impacts. This revision would enable future policy actions to address not only biomass and food-related soil impacts but also non-biomass related influences such as pesticides, mining activities, infrastructure developments (e.g., for tourism), and climate change effects. It may also be beneficial to consider the impact of exported soil amendments (e.g., herbicides, pesticides) and waste (resulting e.g. in landfills) from the EU on soils outside the European Union.

KG2: There is no standard soil footprinting methodology

Even at the EU level, assessing soil health across the EU remains challenging due to the lack of a legal reporting requirement, a unified definition, and standardized measurement methods. There are updated environmental footprint methods available, where land use transformation is linked to four soil properties, with a composite indicator addressing biotic production, erosion resistance, groundwater regeneration and mechanical transformation, developed by JRC. This could be a good starting point to standard soil footprint methodology development. Even if standardized soil data from non-EU countries became available (comparable to the LUCAS datasets in the EU), a significant knowledge gap remains. This gap involves identifying the specific impacts of the EU on soil health observations and further regionalizing these impacts to specific countries.

Additionally, there is a need to differentiate between human and natural impacts, as well as between non-biomass and biomass-related human impacts. As clear from the state-of-the-art, the term footprint can also cause a lot of confusion, since multiple different footprint methodologies have been developed, ranging from product, consumption, land, water to environmental footprints. If a solid 'soil' footprint needs to be developed from this, it is absolutely necessary to also focus here on achieving a consistency of approaches. What is a soil footprint?

KG3: Trade-offs between soil impacts

The foot-printing objective of the Soil Mission targets multiple soil impacts lumped together, unlike the other Soil Mission objectives, which are Europe-oriented and aim for one specific soil function. As a result, a new challenge will arise, with trade-offs between regional (e.g. water cycle, land management, …) and global impacts (e.g. climate change, food security) and between different key focal impact areas, e.g. carbon sequestration and biodiversity. Even if a clear baseline for some functions is established, there will always be trade-offs with other functions (Zwetsloot et al. 2020). A sound methodology for assessing these trade-offs will have to be defined, maximizing synergies and potentially prioritizing certain soil functions in certain areas, based on clear criteria. Here, it is clear that prioritization should not select one perspective and discard the others.

KG4: Scale issues

How we move from case studies to a baseline for global EU impact? How do we link the changes in soil to EU policy and actions, and how do we distinguish EU impact from other local and global impacts? Here is also a matter of scale: at which scale will it be possible to define the impact/EU action relation?

KG5: Impact of local and broader outside EU policy and soil governance

The EU footprint, and any actions related to reducing it, will also interact with local policy actions, particularly in regard to national definitions of "sustainability". This might complicate both the definition of potential EU remediation actions to be taken, and of footprint establishment. It will be key to carefully map and take into account local policy when defining EU actions.

KG6: Potential benefit of the use of new biotechnology, as well as agro-ecological approaches

The potential of new biotechnology and agro-ecological approaches to lower the footprint of EU food import is currently not studied in detail. This can include e.g. microbial tools (Batista and Singh 2021) and agro-ecology innovation (Hawes et al. 2021).

KG7: Link to other Soil Mission objectives

Other Mission objectives focus on EU soils, mostly, without having to consider global impacts. Risk of EU solutions with a footprint abroad is strong. We need to consider the

potential footprint of actions and of their interactions that will emerge from other Soil Mission objectives, in a footprint analysis. How this can be achieved is currently unclear. Yet, it is clear that the outside-EU footprint objective needs to become an essential part of the soil conversations in Europe. Mechanisms need to be developed to implement the footprint analyses in EU soil policy. A sound coordination of approaches suggested within other Soil Mission objectives with their impact on global footprinting is therefore a key aim for Soil Mission objective 7.

Three Horizon Europe Cluster 6 projects have recently started, aiming to improve EU-African Union cooperation on agroforestry management for climate change adaptation and mitigation (HORIZON-CL6-2024-FARM2FORK-01-10). Agroforestry research is related to soil mission objectives.

- Informed Decision-Making for Agroforestry Systems in Africa through a Network of Living Labs (AfroGrow)
- Strengthening rural livelihoods and resilience to climate change in Africa: innovative agroforestry integrating people, trees, crops and livestock (Galileo)
- Novel WEFE Nexus-based approaches towards agroforestry management in the Greater North African Region (Trans-Sahara)

Engagement within the Think Tank

Process for document preparation

We have organized several meetings with the different key stakeholders involved in drafting the document:

- 04/07/2023: AM, online TEAMS

Present: Michael Obersteiner, Isabelle Verbeke, Dries Roobroeck, Ivan Janssens, Eric Struyf, Jessica Donham, Peter Laszlo

- 05/07/2023: AM, online ZOOM

Present: Orsolya Nyárai, Detlef Gerdts, Ivan Janssens, Eric Struyf

Outcome: Get to know, planning and governance of the TT.

Discussion on key issues, challenges and opportunities that all stakeholders and TT participants identify regarding the overall objective.

- 23/11/2023: AM, online TEAMS

Present: Michael Obersteiner, Dries Roobroeck, Eric Struyf, Vincent Dauby, Peter Laszlo, Orsolya Nyárai, Detlef Gerdts, Mirco Barbero

Outcome: Preparation of roadmap and scoping document for Barcelona meeting, to ensure effective discussions.

- 5/12/2023, 6/12/2023 Barcelona

Intensive discussion with stakeholders for this TT (present: Detlef Gerdts, Orsolya Nyárai, Eric Struyf, Vincent Dauby) and other TTs on the linkages of the Mission objective to other Mission goals, and identification of key challenges and knowledge gaps associated to achieving the Mission objectives.

- 28/06/2024, 3/07/2024, AM, online TEAMS

Discussion on prioritization among the identified knowledge gaps (present: Detlef Gerdts, Orsolya Nyárai, Eric Struyf, Ivan Janssens, Gerry Lawson, Ellen Fay; Mirco Barbero, Peter Laszlo), resulting in the identification of 3 key steps necessary to enable to address this Mission objective successfully, that can serve as a base point to identify key R&I action to roll out.

- 10/10/2024, AM, online TEAMS

Continued discussion on the prioritization, to prepare for the SOLO Sofia stakeholder meeting (present Ellen Fay, Dries Roobroeck, Peter Laszlo, Vincent Dauby, Eric Struyf, Gerry Lawson, Mirco Barbero, Zacharia Asri (intern with Ellen Fay).

- 5/11/2024, 6/11/2024 Sofia

Intensive discussions with Eric S, Ellen Fay, Vicent Dauby and Kostadin Evegniev Atanasov and other TT and stakeholders on the prioritisation of the knowledge gaps and the visualisation of the current TT outcomes.

After the Sofia meeting, there was an intense circulation of this document, with multiple new stakeholders involved. Strong input was provided by new authors Mathis Wackernagel, David Robinson and Arwyn Jones as well as all people already named above, with focus on prioritization and state-of-the-art.

Roadmap: initial knowledge gaps translated into actionable priority knowledge gaps

What is most urgently needed before the EU can start to have a better grip on its soil footprint outside the EU? Reconsidering the earlier research gaps, condensing them into the very essence of what needs to be achieved, triggered a solid consensus among the stakeholders. Compared to other soil Mission objectives, it will be clear that these R&I priority needs are surprisingly basic. The authos consider that a concerted effort to address all five key priority knowledge gaps identified, is key to enabling the first essential steps in achieving a first quantified impact of EU actions on soils worldwide.

1. We need to define current hot-spots of soil footprint for maximum impact

To identify the key impact areas of the European Union (EU) on soil functions, soil health and soil services worldwide, assessing key value chains in food and fibre industries is essential. First, a detailed global map of import of food and fiber commodities into the EU needs to be produced, by providing a total inventory of potential impacted soil surfaces per commodity, per impact region. For each of the imported commodities, imported amounts can be matched to per area productivity potential. Actions should use the most detailed available databases (a first overview of potential databases is given below). Here it is possible to build on practices developed e.g. for EUDR, which works based on a central EU Registry. Another, more advanced pathway can be based on the Land Parcel Identification system (LPIS, European Court of Auditors 2016) in each exporting country, linked to national cadastres.

Subsequently, this map needs to be linked to known effects of agricultural, forestry and agroforestry activity on soil's provision of ecosystem services, both negative and positive (this can be based e.g. on quantification systems developed in EU Horizon projects LANDMARK and BENCHMARKS). The impact will depend on the sustainability of practices applied. Footprinting should distinguish between unsustainable practices, which degrade soil, and sustainable practices, which maintain soil health. Footprints will also need to distinguish whether import of biomass requires land use change (which is typically a driver for e.g. biodiversity loss, soil erosion, soil carbon storage, soil sealing and soil carbon emissions).

In a final step, the theoretical maps produced can be matched against actual observations of soil status in the identified key impact areas. Areas where potential impact is largest, with matching observed persistent changes in soil health, can thus be identified. Remediation actions in these areas can be defined, with immediate potential for assessing the soil health status compared to baseline conditions from earlier observations. Here, it will be essential to take into consideration external factors that can affect outcomes beyond the applied practice(s), e.g. climatic stresses.

It will be essential to implement concrete solutions based on a thorough assessment of the value chains, e.g. through detailed life cycle assessments (LCAs). LCAs provide detailed insights into the environmental impacts associated with each stage of a product's life, from production to disposal. By focusing on soil-related impacts, LCAs can help identify hotspots where soil degradation is most severe. The MRIO studies, as identified earlier, have performed studies that partly reflect the approach above, albeit with following limitations: the studies currently cannot relate specific soils directly to the import and export of commodities, did not focus on soils and offer a large-scale overview of broad sectoral impact. The challenge lies in expanding this broad overview to include multiple soil functions, relating impact to specific soils through detailed value chain analysis, and to relate MRIO outputs to actual observed data. A brief overview of key impact studies of EU (environmental) impact worldwide is summarized below, showing again the current absence of detailed soil impacts (Table 1).

Table 1.
Key impact studies of EU environmental impact worldwide

Study	EU origin region	Outside EU impact region	Study target	Main outcome
Vanham et al. 2023	EU	World	Land footprint Water footprint No soil focus	Challenging to include latest data Strong impact of chosen 'accounting' method
Beylot et al. 2019	EU	World	Environmental footprint No soil focus	Consumption identified as key explanatory variable
Kumeh and Ramcilovic-Suominen 2023	EU	World	Deforestation No soil focus	Current regulations risk shifting responsibility to non-EU countries. Spillover risk
Galli et al. 2023	EU	World	Ecological footprint No soil focus	Food responsible for 1/3 of total ecological footprint
Giljum et al. 2016	EU	World	Focus on material extractionNo soil focus	Strong proportional increase in relative importance of non-EU materials between 1995 and 2011
Zhong et al. 2024	EU	World	Demand for agricultural landNo soil focus	Green Deal spillover effects exceed potential positive effects outside EU
Bruckner et al. 2019	EU	World	Non-food bioeconomyNo soil focus	2/3 of cropland required for EU non-food biomass is outside EU
Cederberg et al. 2019	Sweden	World and other EU	Focus on carbon footprint and pesticide footprint No soil focus	Highlights need for improved spatial data Outside EU impact mainly in Latin America
Kalt et al. 2021	Austria	World and other EU	Origin of biomass consumed No soil focus	Only 7.6 % of biomass originates outside EU
Schwarzmueller and Kastner 2022	World	World	National trade profiles for 191 consumed items No soil focus	Potential to identify key consuming countries where consumption has highest impact

Databases that can potentially be used are (non-exhaustingly) listed below:

- **Food and Agriculture Organization (FAO)** - The FAO collects and disseminates data on agriculture, forestry, fisheries, and land use. Its Global Soil Partnership (GSP) works to improve soil governance and promote sustainable soil management. The FAO's Soil Information System (SIS) and Global Soil Organic Carbon Map (GSOCmap) can be a valuable asset for mapping the EU's global soil impact.
- **International Union for Conservation of Nature (IUCN)** - The IUCN focuses on conservation and sustainable use of natural resources. Its work on ecosystem management and biodiversity, including soil health, provides potentially important data that can be used to assess the impacts of EU-related activities, for example,

through the use of the Red List of Ecosystems, the Land Health Monitoring Framework, the Natural Capital Protocol, or the IUCN STAR Metric.

- **JRC Global Forest Map** - This map synthesizes information on intensive and extensive agricultural use worldwide.
- **World Resources Institute (WRI)** - The WRI provides data and analysis on global resources, including land use and soil health. Tools like the Global Forest Watch and the Aqueduct Project offer potential insight into land degradation and soil conditions.
- **Global Environment Facility (GEF)** - The GEF funds projects related to biodiversity, climate change, land degradation, and sustainable land management. The generated data could be valuable for the assessment.
- **Intergovernmental Panel on Climate Change (IPCC)** - The IPCC provides scientific assessments on climate change, including its impacts on soil health. Its reports and data can offer insights into how EU-related activities contribute to soil degradation and what mitigation measures can be adopted.
- **International Soil Reference and Information Centre (ISRIC)** - ISRIC provides global soil data and information. Its World Soil Information service offers a comprehensive database
- **European Soil Data Centre (ESDAC)** - ESDAC, managed by the JRC, provides comprehensive soil data and information. It supports the development of soil policies and monitoring programs across Europe, aiding in systematic soil function assessment.
- **EUSO Dashboard** - The EUSO Soil Degradation Dashboard is an online tool developed by the JRC to monitor and assess soil degradation across Europe by providing data on factors like erosion, organic carbon loss, and land use.
- **OECD (Organisation for Economic Cooperation and Development)** - The OECD produces a wide range of research, reports, and statistics on various economic and social issues. It regularly publishes benchmarks like the OECD Economic Outlook, and the OECD Better Life Index. Data are e.g. available for nutrient (im)balance; The nutrient balance is defined as the difference between the nutrient inputs entering a farming system (mainly livestock manure and fertilisers) and the nutrient outputs leaving the system (the uptake of nutrients for crop and pasture production). A nutrient deficit (negative value) indicates declining soil fertility. A nutrient surplus (positive data) indicates a risk of polluting soil, water and air.
- **Africa Knowledge Platform** - The Africa Knowledge Platform is an initiative launched by the JRC in collaboration with various partners to consolidate and disseminate knowledge, data and resources pertinent to Africa's development. Specific focus areas include sustainable development and environmental conservation, i.e. climate change mitigation, sustainable agriculture and natural resource management.

2. We need a harmonized and regionalized soil health assessment methodology, incl. trade-offs.

3. We need to disentangle food and fibre impact from other impact

Reminiscent of the EU Soil Monitoring Law (SML) that is intended to provide a comprehensive framework for monitoring soil health across the European Union, an overall framework has to be available of key soil ecosystem services to assess, and how to assess them, for outside EU soil footprinting and assessment of current impact and future potential improvements. Like the EU SML (which is currently not yet approved by EU countries), it can build on existing initiatives and ensure systematic, standardized, and obligatory soil monitoring. This standardized footprinting methodology can be linked to actions taken under priority knowledge gap 1, enabling to install a solid on-the-ground monitoring of effective soil impact related to export of key agricultural commodities to the European Union, with a primary focus on identified hotspots of European impact. This standard footprinting can be based on a solid range of already existing national and international initiatives to assess soil health and soil ecosystem services, of which a non-limiting overview is provided below. Both KGs are interlinked here, because the narrow focus of the Soil Mission on food and fiber import impact will require distinguishing these impacts from other impacts. As emphasized earlier, not all authors agree with this narrow focus, yet given its current central appearance in mission objective 7, it will need to be addressed.

- **EU Common Agricultural Policy (EU CAP)**

Under the EU CAP, farmers receiving direct payments must comply with Good Agricultural and Environmental Conditions (GAEC) standards. If they receive eco-scheme payments the expectations are greater, and higher still for some investment or agri-environment climate payments in Pillar II.

- **EU CAP Network**

The EU CAP Network is set up to support the implementation of the CAP Strategic Plans.The Network is a forum for National CAP Networks, organizations , administrations, researchers, entrepreneurs and practitioners to share knowledge and information about agriculture and rural policy. The Network has three main objectives: design and implementation of the CAP Strategic Plans (CSPs), support innovation and knowledge exchange including EIP AGRI, and evaluation and monitoring of the CSPs. The EU CAP Network also operates thematic Focus Groups with temporary groups of selected experts focusing on a specific subject, sharing knowledge and experience, for example on ‘Reg enerative agriculture for soil health’.

- **Germany**

Germany has implemented the Federal Soil Protection Act (BBodSchG) and the Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV), which mandate systematic soil monitoring and protection measures.

- **United Kingdom**

The UK has several statutory instruments that protect soil health, such as England's Agriculture Act which allows the Government to pay farmers to protect and improve soil quality and the Environmental Improvement Plan, which sets national targets for sustainably managed soils.

- **France**

France's national policy on soil protection is embedded in various legislative acts, including the Environmental Code. The country has developed a National Soil Monitoring Network (Réseau de Mesures de la Qualité des Sols, RMQS) that systematically assesses soil quality across different land uses.

- **Hungary**

The Hungarian Soil Conservation Action Plan (HSCAP) focuses on the protection of soil under agricultural cultivation. The document proposes a division of labour and responsibilities between the farmers and the state for the long-term conservation of soils and the maintenance of fertility along food chain safety principles. The HSCAP identifies the most important elements of soil protection, as follows: reasonable land use, preservation of high-quality lands, lands that are already deteriorating and that are targeted as those for improvement of related conditions; termination of soil degradation processes; maintenance and improvement of soil water balance and moisture circulation; control over substances introduced into the soil, nutrient-containing and municipal and industrial by-products.

- **LUCAS (Land Use/Cover Area frame statistical Survey)**

LUCAS assesses land use, land cover, and soil characteristics across the EU. The survey includes systematic soil sampling and analysis.

- **Australia**

Australia's National Soil Strategy aims to ensure sustainable soil management through systematic monitoring and assessment. The strategy is supported by the National Soil Monitoring Program, which provides regular and comprehensive data on soil health and functions.

- **United States**

The United States has several programs dedicated to soil assessment, including the Natural Resources Conservation Service (NRCS) and the Soil Health Division within the Department of Agriculture (USDA). These programs systematically monitor soil health and promote sustainable soil management practices.

- **BIO-EAST**

BIOEAST, the Central and Eastern European Initiative for Knowledge-based Agriculture, Aquaculture, and Forestry in the Bioeconomy is a collaborative initiative involving 11 Central and Eastern European (CEE) countries (from the Baltic through Central Europe to the Balkans) aiming to develop sustainable bioeconomy in the region. It has supported the knowledge-based interconnection of policies on biomass production and processing on a regional scale, as well as the strengthening of research and innovation capacities in Central and Eastern Europe. 11 country-specific studies have already been completed, which individually analyse the potential and development opportunities of the macro-region's biomass-based economy, in order to formulate common knowledge needs and priorities for a more efficient exploitation of the potential of bio-based resources in the countries of the region. The research and innovation agenda developed will greatly facilitate joint thinking and mutually supportive action between science and practice, which could lead to a more sustainable and secure use of resources in the future.

- **FAO**

The FAO Soils portal provides access to various soils information, including a section dedicated to making global, regional and natonal maps and databases available.

There is an essential need for the footprint soil health assessment framework to be regionalized and standardized, enabling to capture complex, site-specific trade-offs among various soil ecosystem services. It will be challenging to standardize methodologies across diverse regions while accommodating local specificities and trade-offs between competing ecosystem services (Lehmann et al. 2020). They emphasize the need for robust, scalable indicators that integrate biological, chemical, and physical properties, where this integration is often underdeveloped. Balancing the demand for rapid, cost-effective assessments with the need for depth and accuracy will be an additional potential hurdle. Translating assessments into actionable policies that consider the socio-economic and ecological trade-offs at regional level will be essential.

Robinson et al. (2024), building on five decades of experience from the UK Centre for Ecology & Hydrology (UKCEH) Countryside Surveys (CS) of Great Britain and Northern Ireland, Welsh Government, the Environment and Rural Affairs Monitoring and Modelling Programme (ERAMMP) and the England Ecosystem Survey (EES) monitoring, underscore the importance of long-term soil monitoring. Principles of robust statistical sampling, co-location of soil and vegetation sampling, and integration into policy frameworks will have to be adapted, aligned with the Driver-Pressure-State-Impact-Response (DPSIR) model. The study highlights the need to balance regional specificities with standardized metrics for assessing soil ecosystem services. This includes leveraging existing initiatives like LUCAS and integrating cost-effective, scalable soil indicators (e.g., pH, soil organic carbon) linked to ecosystem services.

4. We need to assess potential of other EU footprinting and beyond EU impact initiatives for soils

The European Union's commitment to addressing climate change and environmental degradation has spurred the development of comprehensive policies aimed at reducing carbon emissions, preserving biodiversity, and promoting sustainable practices, including outside the EU. Mechanisms such as the Carbon Border Adjustment Mechanism (CBAM), the European Union Deforestation Regulation (EUDR), and the Environmental Management and Audit Scheme (EMAS) are among the most essential. Despite their ambitious goals, challenges persist, including tracing complex supply chains and ensuring compliance with global trade rules. We here below emphasize the importance of maximally leveraging potential soil knowledge already gathered in these mechanisms to kickstart soil footprint quantification.

- **CBAM**

CBAM is the EU policy designed to address carbon leakage, by imposing a carbon price on imports of goods from non-EU countries. CBAM aims to ensure that the price of carbon reflects the greenhouse gas (GHG) emissions embedded in the production of goods, levelling the playing field between EU producers and their international competitors. It is currently in a transitional phase (2023-2025), and initially only applied to imports of goods whose production is carbon intensive and at most significant risk of carbon leakage: cement, iron and steel, aluminium, fertilisers, electricity and hydrogen. A similar principle for agricultural products could be implemented, that also accounts for soil management practices (e.g., deep tillage vs. no tillage). By placing a carbon price on imported agricultural products, CBAM can incentivize exporters to adopt more sustainable practices that reduce their carbon footprint. In any case, CBAM does not directly relate to or obliges to assess soil impact. Its impact on soil is more of a secondary effect through the promotion of sustainable practices and reduced emissions.

Matthews (2022) provided a first study of the potential of CBAM for targeting carbon footprint of agri-products. It came to a similar conclusion as emphasized by our first essential knowledge gap: "*there would be major practical problems in determining the appropriate level of embedded emissions in imported food products, **given the complexity of food supply chains where ingredients can be sourced from several countries**, all of whom may have climate policies with different levels of ambition. The potential severity of these practical problems will become clearer as experience is gained with the application of the CBAM levy to the narrower range of industrial products envisaged in the CBAM Regulation*."

Europe would also need a statutory carbon accounting scheme, building e.g. on the Agri-ETS that are currently under discussion (European Environmental Bureau 2024), before extending CBAM to agriculture and forestry can be permissible under WTO rules. Recently, the EU commission also hinted on a market-based system to encourage farmers and industry to conserve nature and restore lost biodiversity by putting a price on ecosystems. Here, it was suggested to create new financial tools to compensate farmers

for the extra costs of sustainability and compensate them for taking care of soil, land, water and air. If such a system would be implemented within the EU, an equivalent should be developed for non-EU impact, to ensure that within EU practices do not negatively affect other regions (Von der Leyen 2023).

- **EUDR**

The EUDR aims to minimize the EU's contribution to global deforestation and forest degradation, by ensuring that products placed on the EU market are not linked to deforestation or forest degradation. EUDR covers commodities like soy, beef, palm oil, wood, cocoa, and coffee. The EUDR addresses soil functions more explicitly than CBAM. In Kumeh and Ramcilovic-Suominen (2023), EU actions on deforestation, and their efficiency, was critically evaluated. Also here, the complexity and length of supply chains were indicated as a prime challenge for tracing the origins of commodities. For example, supply chains for products like soy, palm oil, and beef often involve multiple intermediaries and can span numerous countries, complicating efforts to ensure products are deforestation-free. The EU's proposed deforestation regulation emphasizes traceability, requiring companies to provide geographic coordinates of the land used for production. However, implementing such detailed traceability measures is difficult, particularly for commodities sourced from multiple smallholders and mixed production systems.

The authors also indicate that current EU policies primarily focus on improving governance and capacity building in producing countries, which shifts the burden of deforestation onto these nations. This approach often overlooks the EU's role in driving demand for deforestation-linked products and does not adequately address the broader structural issues of overconsumption and market power imbalances. This puts attention to the fact that EU footprint outside EU could probably also be addressed through within EU actions changing consumption patterns.

- **EMAS, CSDD and CSRD**

Soil foot-printing can be considered as an essential part of the ‘EMAS’ Community eco-management and audit scheme, that aims to drive organisations towards circularity and reduce their impact on the environment, albeit not specifically related to non-EU impact. In 2021, updated Environmental Footprint (EF) methods, comprising the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) and Consumption Footprints (CF) were published by the EU Commission. EF methods are based on life cycle assessment. The EF relates to soil in the land use impact category. Here, for land occupation, impact is related to changes in soil quality multiplied by area and duration. Land transformation considers the extent of changes in land properties and the area affected (changes in soil quality multiplied by the area). Recommendations specifically refer to the ‘Soil quality index’. This index is the result of the aggregation, performed by JRC, of 4 indicators (biotic production, erosion resistance, mechanical filtration and groundwater replenishment) provided by the LANCA model for assessing impacts due to land use, as reported in De Laurentiis et al. (2019). The LCI (life cycle

inventory) provides specific recommendations for data collection for nitrogen emissions from soil related to fertilizers, soil impact of heavy metals and pesticides, soil carbon emissions and soil carbon stocks. In this corporate framework, if avoiding soil footprint becomes institutionalized in EU, specific soil directives could become part of the Corporate Sustainability Due Diligence Directive (CSDD), that aims to ensure that companies within the EU and those supplying the EU market take responsibility for identifying, preventing, and addressing adverse environmental and human rights impacts throughout their value chains. This also relates to the Corporate Sustainability Reporting Directive (CSRD), which aims to enhance and standardize sustainability reporting by companies operating within the EU.

- **EU Taxonomy regulation and the EU sustainable finance framework**

The EU taxonomy regulation is a classification system that defines criteria for economic activities that are aligned with a net zero trajectory by 2050 and the broader environmental goals other than climate. By embedding soil criteria in the regulation, this could promote explicit positive soil action. Here, there is a potential link to natural capital assessment and the System of Environmental Economic Accounting (SEEA), a statistical system that brings together economic and environmental information into a common framework to measure the condition of the environment. Its suitability to support regional, national and global monitoring efforts is being increasingly recognized in forums such as the UN Sustainable Development Goals, the Aichi Biodiversity Targets and the development of a Natural Capital Protocol (Obst 2015). Linking global economic models to biophysical models could also be used to assess the economic impacts of the soil degradation, as performed for soil erosion by Sartori et al. (2019).

- **Nature Restoration Law**

Some indicators stipulated within the EU NRL directly relate to soil health: stock of organic carbon in cropland mineral soils and share of agricultural land with high-diversity landscape features. Maximal complementarity to soil targets defined for soil footprinting should be envisaged.

- **Voluntary mechanisms**

Voluntary compliance mechanisms such as the Rainforest Alliance and the Roundtable on Sustainable Palm oil already consider soil impacts directly or indirectly as part of their commitment to promoting sustainable agriculture and forestry practices. Their experience should also be considered as a valuable input for EU footprinting, and maximal usage of these and other voluntary mechanisms envisaged.

- **UNFCCC LULUCF carbon accounting**

The emission calculation and the mitigation potential as currently used in the UNFCCC LULUCF accounting has the potential to directly link CO2 emissions to land use changes.

Based on the more detailed priority knowledge gaps defined above, following steps are key to achieve before a detailed EU footprint assessment on soils outside EU is possible:

- Develop a comprehensive mechanism for food- and fiber product supply chain impact assessment, that can link specific EU imports to specific soils affected. Based on this exercise, key commodities for more detailed soil impact study can be selected. This can be based on current efforts in CBAM and EUDR to relate EU imports to respective carbon emissions and deforestation. However, it is clear that also here, the complex supply chains are considered as a major critical challenge.
- Perform an assessment of soil impacts of the priority imported food- and fiber products on soils outside the EU. Hereto, a common method for assessing footprint has to be developed, potentially based on a wide range of existing soil footprinting standards, and on the soil quality index as proposed by JRC. Here, first specific study cases can be used to identify key soil impacts to be assessed.
- Given recent drawbacks with the implementation of e.g. the EUDR, and e.g. the complexity of extending the CBAM system to agriculture through AGRI-ETS, it will be important to aim for both realistic short-term ambition levels and more ambitious long-term ambition. This accounts for both objectives defined within the EU footprinting objective: establish the EU's global soil footprint in line with international standards, reduce the impact of EU's food, timber and biomass imports on land degradation elsewhere without creating trade-offs. A realistic pathway forward could be to focus initial footprinting only on key impact areas (e.g. priority knowledge gap 1), focus only on key soil ecosystem services and build on other initiatives (cfr. priority knowledge gaps 2 and 3). Still, long-term ambition has to remain high-level, with an accounting method that assesses within EU impact and outside EU impact in a similar way, building e.g. on the methodology that will be defined in the SML.

5. We need to define spill-over effect of EU Green Deal and other EU actions, decisions, policy

Actions within the EU that influence consumption patterns, soil stewardship, or trade relations have the potential to impact the EU's global soil footprint. These effects manifest through changes in value chains, traded biomass commodities, or the possible relocation of production to non-EU countries. An et al. (2024) explored the often-overlooked spillover effects between 'green initiatives' implemented concurrently. By analyzing 15 case studies across different countries worldwide, the authors identify both beneficial and detrimental spillover effects, revealing how one initiative can amplify or undermine another's outcomes. These findings underscore the necessity for integrated and coordinated environmental policymaking. Leveraging the spillover dynamics is crucial to enhance global conservation effectiveness, to minimize unintended harm, and to align with sustainable development goals.

To avoid negative impacts of EU actions on soils outside the EU, the Soil Mission acknowledges the need for global alignment of the soil health concept and actions to

reduce and minimize the soil footprint outside the EU from imports of food, biomass, and timber. Zhong et al. (2024) further underscore that the European Green Deal (EGD) may inadvertently increase ecological harm by driving demand for an additional 23.9 million hectares of agricultural land outside the EU by 2030. This underscores the need for coordinated global policies to mitigate spillover effects. Keane et al. (2024) highlight the risks of increased compliance costs for developing nations, potentially limiting market access and impacting trade competitiveness for least developed countries (LDCs). Moreover, ensuring that deforestation-linked imports comply with stringent EU regulations introduces barriers that must be addressed through tailored capacity-building initiatives. Aligning the Soil Mission with broader international frameworks and supporting traceability systems in LDCs will be essential to minimize unintended ecological and socio-economic consequences of EU actions.

At present, the other sub-objectives of the Soil Mission primarily address specific actions and knowledge gaps necessary to improve soil health and awareness within the EU. In contrast, the footprint objective consolidates diverse issues such as soil erosion, carbon loss, soil sealing, pollution, degradation, and other soil impacts into a singular overarching goal for non-EU impacts. This broad scope complicates the footprint objective, as any proposed actions under other Soil Mission objectives (and by extension, other SOLO TT initiatives) could potentially generate spillover effects on the EU footprint.

To address this complexity, a framework must be developed to link EU soil and environmental sustainability policies with their external impacts. We argue that this framework should build on other priority knowledge gaps. A robust definition of the current footprint and a reliable methodology to assess it are essential for devising future actions to mitigate the footprint, both within non-EU countries and within the EU itself (Fig. 1).

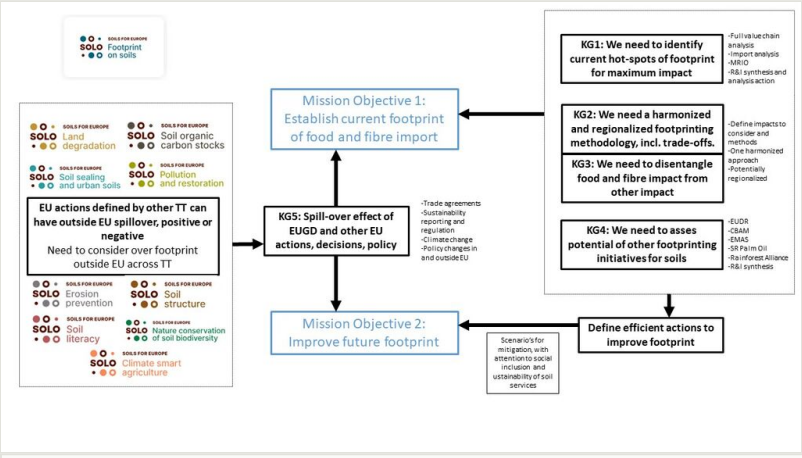

Figure 1. doi

Overview of TT priority knowledge gaps and actions.

Prioritization

During the SOLO stakeholder meeting in Sofia (November 2024) and during an online consultation with SOLO stakeholders, it was asked to prioritize among these knowledge gaps.

This resulted in the following result, with in total 222 votes submitted by 74 stakeholders and SOLO project members.

1. Defining a harmonized footprinting methodology: 26,6% of votes
2. Defining spill-over effects of EU actions and policy: 22.5 % of votes
3. Defining hot-spot impact regions: 20.3 % of votes
4. Assessing readiness of other footprinting schemes for soil footprint: 15.8 % of votes
5. Disentangle food-fibre impacts from other impacts: 14.9 % of votes

The prioritization shows that there is quite a strong consensus among stakeholders that all priority knowledge gaps are similarly important, with the strongest priority given to defining a harmonized soil footprinting methodology.

Roadmap table

Table 2 provides a roadmap overview and can be found under Suppl. material 1

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References

- An L, Liu J, Zhang Q, Song C, Ezzine-de-Blas D, Dai J, Zhang H, Lewison R, Bohnett E, Stow D, Xu W, Bryan B (2024) Global hidden spillover effects among concurrent green initiatives. Science of The Total Environment 917 https://doi.org/10.1016/j.scitotenv.2024.169880
- Batista B, Singh B (2021) Realities and hopes in the application of microbial tools in agriculture. Microbial Biotechnology 14 (4): 1258-1268. https://doi.org/10.1111/1751-7915.13866
- Beylot A, Secchi M, Cerutti A, Merciai S, Schmidt J, Sala S (2019) Assessing the environmental impacts of EU consumption at macro-scale. Journal of Cleaner Production 216: 382-393. https://doi.org/10.1016/j.jclepro.2019.01.134
- Bruckner M, Häyhä T, Giljum S, Maus V, Fischer G, Tramberend S, Börner J (2019) Quantifying the global cropland footprint of the European Union's non-food bioeconomy. Environmental Research Letters 14 (4). https://doi.org/10.1088/1748-9326/ab07f5

- Cederberg C, Persson UM, Schmidt S, Hedenus F, Wood R (2019) Beyond the borders – burdens of Swedish food consumption due to agrochemicals, greenhouse gases and land-use change. Journal of Cleaner Production 214: 644-652. https://doi.org/10.1016/j.jclepro.2018.12.313
- De Laurentiis V, Secchi M, Bos U, Horn R, Laurent A, Sala S (2019) Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA. Journal of Cleaner Production 215: 63-74. https://doi.org/10.1016/j.jclepro.2018.12.238
- De Laurentiis V, Orza V, Sala S (2024) Modelling the land footprint of EU consumption, Publications Office of the European Union. Publications Office of the European Union. URL: https://publications.jrc.ec.europa.eu/repository/handle/JRC137757
- European Commission: Joint Research Centre, Fernandes-Ugalde O, Scarpa S, Jones A, Eiselt B (2021) LUCAS soil 2022 – ISSG planning document. EC JRC. Publications Office. URL: https://op.europa.eu/en/publication-detail/-/publication/00e8735d-4da1-11ec-91ac-01aa75ed71a1/language-en
- European Court of Auditors (2016) The Land Parcel Identification System – A useful tool to determine the eligibility of agricultural land – but its management could be further improved. Special report No 25, 2016. Publications office of the EU. URL: https://op.europa.eu/en/publication-detail/-/publication/11049e0e-9a82-11e6-9bca-01aa75ed71a1/language-en
- European Environment Agency (EEA), Larsen W, Lung T (2020) Is Europe living within the limits of our planet? – An assessment of Europe's environmental footprints in relation to planetary boundaries. EEA. Publications Office. https://doi.org/10.2800/890673
- European Environmental Bureau (2024) Reducing emissions from agriculture: Reflection on the potential design and scope of an EU Emissions Trading System for agriculture. URL: https://eeb.org/library/reducing-emissions-from-agriculture-reflection-on-the-potential-design-and-scope-of-an-eu-emissions-trading-system-for-agriculture/
- Galli A, Antonelli M, Wambersie L, Bach-Faig A, Bartolini F, Caro D, Iha K, Lin D, Mancini MS, Sonnino R, Vanham D, Wackernagel M (2023) EU-27 ecological footprint was primarily driven by food consumption and exceeded regional biocapacity from 2004 to 2014. Nature Food 4 (9): 810-822. https://doi.org/10.1038/s43016-023-00843-5
- Giljum S, Wieland H, Lutter S, Bruckner M, Wood R, Tukker A, Stadler K (2016) Identifying priority areas for European resource policies: a MRIO-based material footprint assessment. Journal of Economic Structures 5 (1). https://doi.org/10.1186/s40008-016-0048-5
- Hawes C, Iannetta PM, Squire G (2021) Agroecological practices for whole-system sustainability. CABI Reviews https://doi.org/10.1079/pavsnnr202116005
- Kalt G, Kaufmann L, Kastner T, Krausmann F (2021) Tracing Austria's biomass consumption to source countries: A product-level comparison between bioenergy, food and material. Ecological Economics 188 https://doi.org/10.1016/j.ecolecon.2021.107129
- Keane J, Agarwal P, Mendez-Parra M, Debowicz D (2024) Avoiding a 'green squeeze': supporting Least Developed Countries navigate new greening trade measures. ODI Global. URL: https://odi.org/en/publications/avoiding-a-green-squeeze-supporting-least-developed-countries-navigate-new-greening-trade-measures/
- Kumeh EM, Ramcilovic-Suominen S (2023) Is the EU shirking responsibility for its deforestation footprint in tropical countries? Power, material, and epistemic inequalities in the EU's global environmental governance. Sustainability Science 18 (2): 599-616. https://doi.org/10.1007/s11625-023-01302-7

- Lehmann J, Bossio D, Kögel-Knabner I, Rillig M (2020) The concept and future prospects of soil health. Nature Reviews Earth & Environment 1 (10): 544-553. https://doi.org/10.1038/s43017-020-0080-8
- Matthews A (2022) Trade policy approaches to avoid carbon leakage in theagri-food sector,. URL: https://left.eu/app/uploads/2023/02/GUE-Study-TRADE-Carbon-leakage.pdf
- Obst C (2015) Account for soil as natural capital. Nature 527 (7577): 165-165. https://doi.org/10.1038/527165b
- Robinson D, Bentley L, Jones L, Feeney C, Garbutt A, Tandy S, Lebron I, Thomas A, Reinsch S, Norton L, Maskell L, Wood C, Henrys P, Jarvis S, Smart S, Keith A, Seaton F, Skates J, Higgins S, Giuffrè G, Emmett B (2024) Five decades' experience of long-term soil monitoring, and key design principles, to assist the EU soil health mission. European Journal of Soil Science 75 (5). https://doi.org/10.1111/ejss.13570
- Sala S, De Laurentiis V, Orza V (2025) Land footprint estimates model results (model version 2.0). European Commission. Joint Research Centre (JRC). URL: https://data.jrc.ec.europa.eu/dataset/93243935-b894-4a82-afb7-450dc2d712e7
- Sartori M, Philippidis G, Ferrari E, Borrelli P, Lugato E, Montanarella L, Panagos P (2019) A linkage between the biophysical and the economic: Assessing the global market impacts of soil erosion. Land Use Policy 86: 299-312. https://doi.org/10.1016/j.landusepol.2019.05.014
- Schwarzmueller F, Kastner T (2022) Agricultural trade and its impacts on cropland use and the global loss of species habitat. Sustainability Science 17 (6): 2363-2377. https://doi.org/10.1007/s11625-022-01138-7
- van der Putten W, Bardgett R, Farfan M, Montanarella L, Six J, Wall D (2023) Soil biodiversity needs policy without borders. Science 379 (6627): 32-34. https://doi.org/10.1126/science.abn7248
- Vanham D, Bruckner M, Schwarzmueller F, Schyns J, Kastner T (2023) Multi-model assessment identifies livestock grazing as a major contributor to variation in European Union land and water footprints. Nature Food 4 (7): 575-584. https://doi.org/10.1038/s43016-023-00797-8
- Wackernagel M, Hanscom L, Jayasinghe P, Lin D, Murthy A, Neill E, Raven P (2021) The importance of resource security for poverty eradication. Nature Sustainability 4 (8): 731-738. https://doi.org/10.1038/s41893-021-00708-4
- Zabel F, Delzeit R, Schneider J, Seppelt R, Mauser W, Václavík T (2019) Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. Nature Communications 10 (1). https://doi.org/10.1038/s41467-019-10775-z
- Zhong H, Li Y, Ding J, Bruckner B, Feng K, Sun L, Prell C, Shan Y, Hubacek K (2024) Global spillover effects of the European Green Deal and plausible mitigation options. Nature Sustainability 7 (11): 1501-1511. https://doi.org/10.1038/s41893-024-01428-1
- Zwetsloot M, van Leeuwen J, Hemerik L, Martens H, Simó Josa I, Van de Broek M, Debeljak M, Rutgers M, Sandén T, Wall D, Jones A, Creamer R (2020) Soil multifunctionality: Synergies and trade-offs across European climatic zones and land uses. European Journal of Soil Science 72 (4): 1640-1654. https://doi.org/10.1111/ejss.13051

Supplementary material

Suppl. material 1: Table 2 - Roadmap overview doi

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