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# Systems knowledge for sustainable soil and land management

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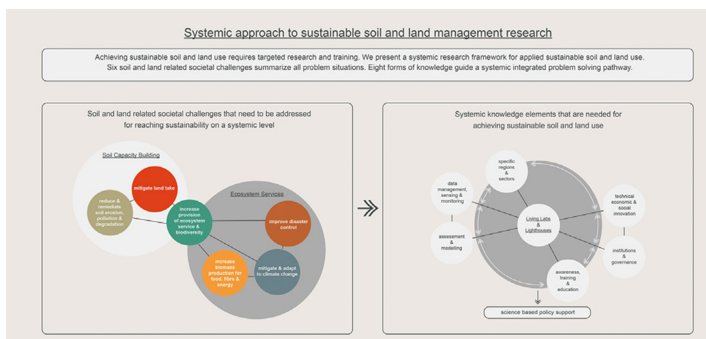
## HIGHLIGHTS

- Sustainable soil and land use is pivotal for of many Sustainable Development Goals.
- Achieving sustainable soil and land use requires targeted research and training.
- We present a systemic research framework for applied sustainable soil and land use.
- Six soil and land related societal challenges summarize all problem situations.
- Eight forms of knowledge guide a systemic integrated problem solving pathway.

## GRAPHICAL ABSTRACT

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## ABSTRACT

While soils and land are pivotal elements of many Sustainable Development Goals (SDGs) and societal challenges, they face degradation and reduction of related functions and services worldwide. Societal demands on soils and land are increasing, including contributions to climate change mitigation and adaptation, ecosystem services, biodiversity and biomass production for food, feed, fiber and energy. This adverse combination of reducing capacities and increasing demands requires rapid transition towards sustainable soil and land management that mitigates trade-offs and creates synergies. Likewise, a transformation of soil and land research is required to scientifically support the sustainable transformation.

Based on a literature analysis combined with engagement of soil and land scientists, we developed a systemic research framework for sustainable soil and land management to support the implementation of the Horizon Europe Mission "*A Soil Deal for Europe*". The framework summarizes soil and land related topics into six societal challenges and associates them with eight knowledge types that outline integrated research for development and implementation of sustainable soil and land management. We propose that research should be aligned with living labs and lighthouses to leverage local solutions, innovation, training and education. We outline the role of experimentation, data analysis, assessment, modelling and the importance of research for institutions, governance and policy support. For encouraging a swift transition towards a systems approach for sustainable soil and land management, we concluded that among all knowledge types, those addressing socio-economic interrelations with soil health and related policies currently represent the biggest bottleneck.

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## 1. Introduction

Soils are the basis for a variety of important functions, ecosystem services and socio-economic activities, including biomass production (e.g. terrestrial ecosystems, food, fodder, fiber, bio-based energy), climate gas fluxes of carbon dioxide ($CO_2$), nitrous oxide ($N_2O$) and methane ($CH_4$), water cleaning, storage and supply, foundation for constructions, supply of construction material, as well as the provision of aesthetic environments that provide habitats, recreation and inspiration to people (Schirpke et al., 2017; Helming et al., 2018b). The achievement of many United Nations Sustainable Development Goals (SDGs) depends either directly or indirectly on soil functions, land use and management (Bouma et al., 2019; Tóth et al., 2018). The SDGs address diverse issues inherently linked to soil and land, such as food security (SDG 2) (FAO, 2018), life on land (SDG 15) (FAO et al., 2020), climate action (SDG13) (IPCC, 2019), clean water (SDG 6) (UN, 2018), and resource efficiency (SDG 12) (FAO and ITPS, 2015). Both the quality and persistence of soil functions (Schulte et al., 2015) and the achievement of soil dependent SDGs largely rely on soil health (Lal et al., 2018; Bonfante et al., 2020). Accordingly, the European Commission (EU) has defined *Soil Health and Food* as one of its five overarching missions ("*A Soil Deal for Europe*") for the new Horizon Europe Framework Program of Research and Innovation from 2021 to 2027, in order to address the SDGs and the Green Deal together with the EU Soil Strategy (EC, 2021). The Horizon Europe Mission "A soil deal for Europe" defines soil health as "*the continued capacity of soils to support ecosystem services, in line with the Sustainable Development Goals and the Green Deal*" (Veerman et al., 2020).

Over the last decades, two major soil and land related trends have been observed within the EU and worldwide: (i) an increase in consumer and industry demands for soil-based production of food, feed, fiber and bio-based energy (Camia et al., 2018; FAO, 2020), and (ii) a decrease in soil health and ongoing soil degradation over large areas (~33% of the global land) (FAO and ITPS, 2015; Gomiero, 2016; Veerman et al., 2020). While these two processes seem to be antagonistic, they are closely linked to each other. Increasing demands lead to an overexploitation of soil resources, increase of competition for land (land grabbing) and land use change (e.g. deforestation, ploughing of grasslands) (Alexander et al., 2015; Ramankutty et al., 2018; Erb et al., 2016). This often results in soil degrading processes such as erosion, compaction, salinization, pollution, acidification, soil organic carbon decline and biodiversity loss (Ramankutty et al., 2018; Borrelli et al., 2017). In addition, less land is available for production due to urbanization and infrastructure development (Prokop and Jobstmann, 2011). Currently, at least one third of the global land is considered as "moderately to highly degraded", while climate change intensifies land degradation, for example through higher frequency and severity of heavy rainfall, floods and droughts, wind, permafrost thaw, salinization due to sea-level rise, wave action, or inappropriate irrigation (EC, 2006; IPBES, 2018; IPCC, 2019; FAO and ITPS, 2015).

Land use types such as agriculture, forestry, urban or industrial soil use build the bridge between the resource 'soil' and anthropogenic activities. While *land* describes the terrestrial surface area of the Earth that is not permanently under water, *soil* represents the unconsolidated upper body of the land surface in which mineral particles, organic matter, water, air and living organisms interact. Soil health management plays a growing role in climate change mitigation and adaptation (IPCC, 2019; Smith et al., 2020), flood control (Whitfield, 2012), biomass production (FAO and ITPS, 2015), food security and safety (FAO et al., 2018), resource efficiency (FAO and ITPS, 2015), and conservation of biodiversity (Zhang et al., 2020). In summary, healthy soils are fundamental for sustainable development.

While the bio-physical importance of sustainable soil and land management is rather clear, achieving soil health requires major adaptations of socio-economic activities, such as food and fiber production methods (Zwetsloot et al., 2020; Helming and Wiggering, 2013), policies and consumption patterns (Merrigan et al., 2015). The complex interaction between soil and land management and soil health makes it difficult to account for the multitude of important factors (Vogel et al., 2018), while soils themselves exhibit high spatial variations. Developing and enforcing sustainable management practices and policies is complex (Helming et al., 2018a), in particular since land and soil related science, policy, and practice communities are often operating in isolation with little synergies.

Research and innovation (R&I) can contribute to the unravelling of these complex soil and land management systems. Yet, soil and land related research is mainly epistemic and restricted to domains within natural sciences often neglecting the multi-functionality of soils and the complex socio-economic aspects of soil and land management (Amin et al., 2020; Visser et al., 2019; Keesstra et al., 2016). Previously, Vogel et al. (2018) developed a systemic modelling framework that combines indicators for soil functions with detailed process understanding of complex processes in agricultural soils. Helming et al. (2018b) developed an analytical framework for sustainability impact assessment of agricultural soil management on soil functions that combines the concepts of resource use efficiency and ecosystem services. However, a systemic integrated scientific approach to soil science, that includes all land use and management types, and that goes beyond knowledge production, but rather into a more strategic, solution and practice oriented mode is not yet available.

The objective of this article is to develop a systemic research framework for sustainable soil and land management that accounts for all land use and management types and societal challenges related to soil and land. The ambition is to promote holistic, trans-disciplinary and participatory research on sustainable soil and land management including measures towards its practical implementation. We develop the framework on the basis of a literature analysis and with the involvement of soil and land experts. Further, we identify urgent R&I needs for sustainable soil and land management. Our framework should stimulate integration of diverse soil and land management related scientific disciplines and demonstrate the relevance of transdisciplinary methods for a swift transition towards sustainable soil and land management.

## 2. Methods – development of a systemic research framework for sustainable soil and land management

A systemic research framework for sustainable soil and land management was developed through a stepwise development process (Fig. 1). First, we performed a desk study summarizing current soil and land related challenges in order to gain a full overview of the soil and land system. Covering all types of soil and land management of all land use sectors, including agriculture, forestry, protected areas, urban and industrial soil use, our desk study included recent scientific soil and land related reports (2006–2020) from major authorities, international and European strategies in the field of soil and land, as well as key scientific articles (e.g. FAO and ITPS, 2015, Veerman et al., 2020, Ekins et al., 2019, EEA, 2019b, IPCC, 2019; full list in Online Resource 1). Literature and documents were selected using the snowball technique (Ridley, 2012). As a major methodological principle that is facilitated by a number of recent key scientific publications (e.g. Keesstra et al., 2020; Helming et al., 2018b), we linked the concept of multi-functionality of land and soil use (Schulte et al., 2015; Helming and Wiggering, 2013; Adhikari and Hartemink, 2016) to societal targets as expressed in the SDGs.

Based on the gathered information, we created a systemic draft research framework for sustainable soil and land management (here including as well soil and land use sectors such as protected areas that do not necessarily include management). We separated the research framework into two categories: (i) major soil and land related societal challenges oriented along the SDGs and covering the questions of 'what' needs to be addressed; and (ii) science based knowledge types covering the question of 'how' R&I needs to address the challenges in order to achieve sustainable and land soil management on a systemic level.

The draft research framework was further elaborated and validated through engagement of R&I experts during an online workshop. For the online workshop, representatives of 45 ongoing or recently finalized soil and land related H2020 research projects were invited. The workshop took place on 13 January 2021 and was co-organized by the EU Research

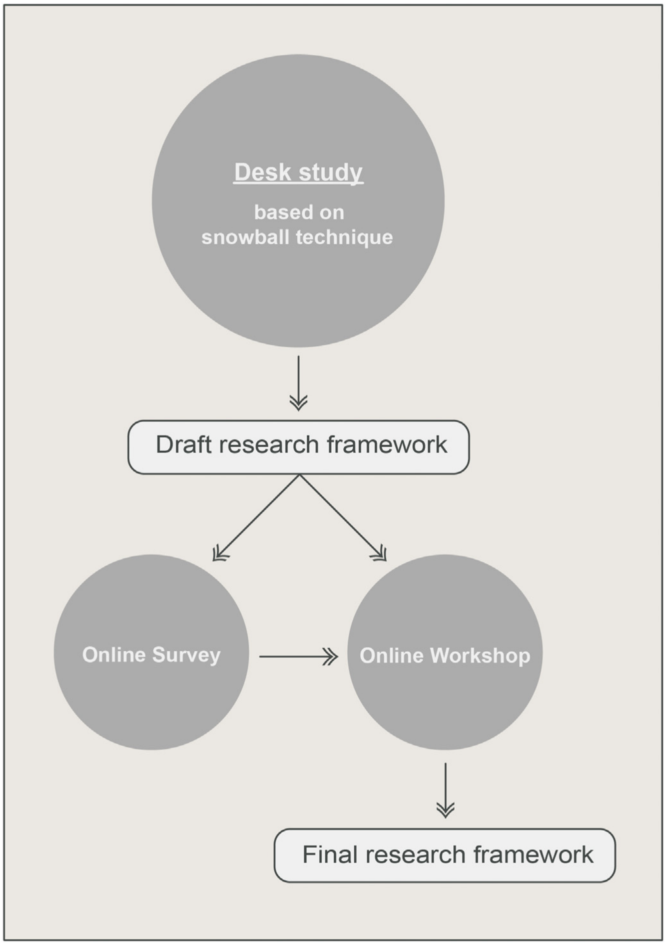


**Fig. 1.** Stepwise workflow of the research framework development through an initial desk study followed by elaboration and validation through R&I stakeholders (online survey and online workshop).

Executive Agency (REA) and the Horizon 2020 Soil Mission Support project. Preceding the online workshop, the R&I experts were invited to fill in an online survey, in which the soil and land related challenges as well as the knowledge types were listed together with questions on respective knowledge needs (Online Resource 2). The survey was available online from 10.12.2020 to 12.01.2021. By filling in the online survey, participants provided information on soil and land related activities of their projects and became acquainted with the draft research framework of soil and land related challenges and knowledge types. In total, 34 R&I experts from 29 projects filled in the online survey (Online Resource 3). The main soil and land use sector addressed by these projects was agriculture (Table 1). Further, the land use sectors forestry, industry, protected areas, and urban land use were covered. This distribution of land use types is representative regarding the research coverage of soil related topics within H2020 projects.

During the online workshops, 32 R&I experts from 28 projects discussed for 30 min in four randomly allocated breakout groups the consistency of the systemic research framework, the coverage of its elements in research projects and respective soil related R&I needs. Participants discussed their ideas verbally and added written comments to the online canvas Padlet. During the discussion, the participants were asked (i) What are the most important soil and land related societal challenges? (ii) What are the most important knowledge types in order to solve these challenges? and (iii) Which combinations of societal challenges and knowledge types are important?

**Table 1**
Soil and land use sectors addressed by 29 soil related H2020 projects that participated in the survey. Some projects covered multiple sectors.

| Soil and land use sector | Number of projects |
|---|---|
| Agriculture | 27 |
| Forestry | 5 |
| Industrial soil use | 4 |
| Protected areas | 3 |
| Soil sealing | 2 |
| Urban soil use | 1 |

## 3. Results – a systemic research framework for sustainable soil and land management

The results of the desk study and the online workshop with R&I experts lead to an overarching classification of soil and land related research topics into six overarching societal challenges (Fig. 2): (1) 'Reduce and remediate soil erosion, pollution and degradation', (2) 'Mitigate land take', (3) 'Increase provision of ecosystem services and biodiversity', (4) 'Increase biomass production for food fibre and energy', (5) 'Mitigate and adapt to climate change', and (6) 'Improve disaster control'. They address preventive measures (i.e. 1, 2, 5, 6) that aim to avoid or counteract direct, or indirect negative processes (e.g. disasters, soil degradation), as well as proactive measures (i.e. 3, 4, 5) that aim at improved soil and land conditions and thus of provided functions (e.g. biomass production, climate resilience). The societal challenges are directly linked to five of the 17 SDGs. Numerous further direct and indirect links exist between SDGs and soil and land management (Lal et al., 2021).

Further, the results revealed eight overarching knowledge types (including forms of knowledge organization) that are associated with the societal challenges: (I) 'Living Labs and Lighthouses', (II) 'Specific regions and sectors', (III) 'Awareness, training and education', (IV) 'Data management, sensing and monitoring', (V) 'Assessment and modelling', (VI) 'Technical, economic and social innovation', (VII) 'Institutions and governance', and (VIII) 'Science based policy support'. The role of 'Living Labs & Lighthouses' was emphasized, since they are special forms of R&I initiatives that address and connect many of the other knowledge types and they are a key strategic element for the implementation of the Horizon Europe Mission "A Soil Deal for Europe" (EC, 2021). The EC (2021) define "*Soil health living labs*" as "*user-centred, placebased and transdisciplinary research and innovation ecosystems, which involve land managers, scientists and other relevant partners in systemic research and co-design, testing, monitoring and evaluation of solutions, in real-life settings, to improve their effectiveness for soil health and accelerate adoption.*"

The identification of knowledge types was guided by the realization gained in sustainability sciences that one needs a complementary combination of different modes of knowledge, i.e. systems knowledge (systemic understanding of complex situations), target knowledge (conceptualisation and contextualisation of problems) and transformation knowledge (how to successfully guide a system transformation), to make scientific evidence useful for practical implementation (Pohl et al., 2017; Gliessman, 2015; König et al., 2021; Hirsch-Hadorn et al., 2008). This includes interdisciplinary interaction of natural and socio-economic sciences (Francis et al., 2003). It also includes trans-disciplinary research approaches that integrate academic and non-academic knowledge sources to a co-creation of knowledge, which in turn requires completely new forms of research organization (or new venues), such as Living Labs (Gascó, 2017; Leminen, 2013) or science policy interfaces (Engels, 2005). For development of practicable solutions, it is further important to foster local research infrastructures and data management in order to account for the uniqueness of places in terms of pedo-climatic and socio-economic conditions, i.e. the diversity of location specific needs (Gliessman, 2015; Francis et al., 2003).

### 3.1. Societal challenges related to soil and land management

#### 3.1.1. Reduce and remediate soil erosion, pollution and degradation

SDG 15 'Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss' is, among other SDGs,

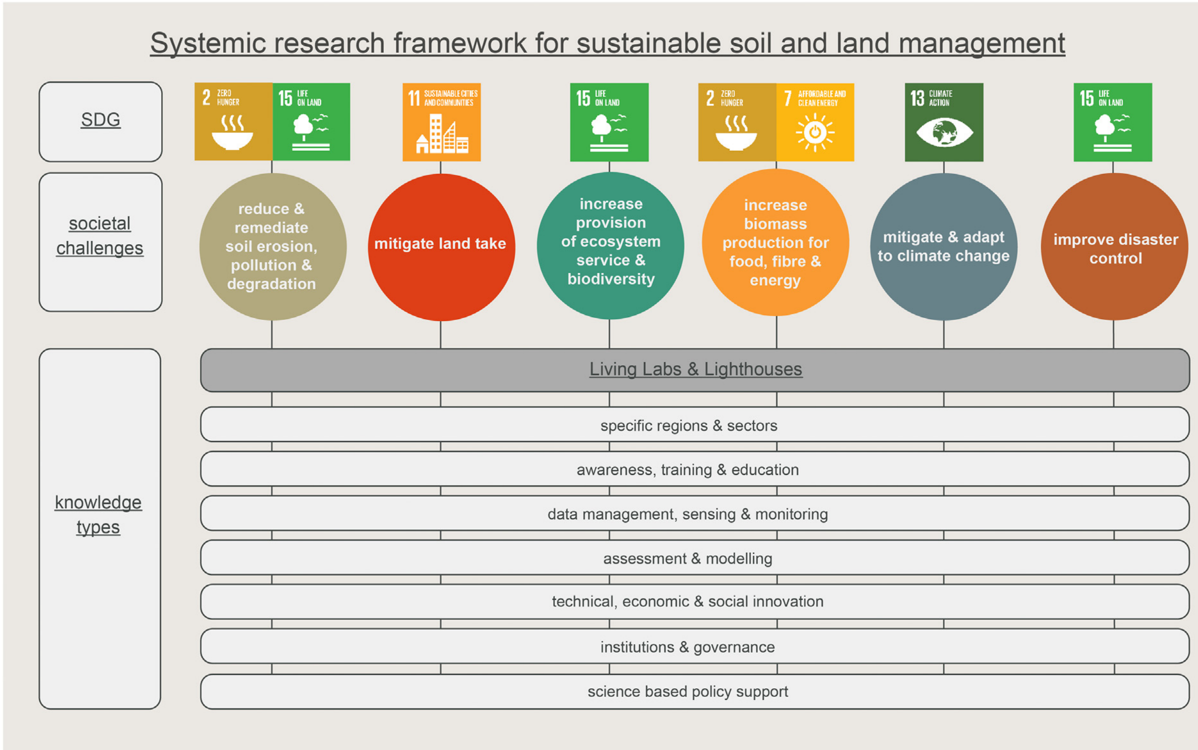


**Fig. 2.** The systemic research framework for sustainable soil and land management, as based on the SDGs and objectives and building blocks of the Horizon Europe Mission on Soil Health and Food (Veerman et al., 2020). The columns represent six major societal challenges together with their corresponding SDGs. The rows show the different types of scientific knowledge and knowledge organization forms needed in order to ensure practical transition towards sustainable soil and land management. 'Living Labs & Lighthouses' are emphasized (in blue), since they address and connect many of the other knowledge types. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

closely related to SDG 2 'End hunger, achieve food security and improved nutrition and promote sustainable agriculture'. Healthy, functional soils are the fundamental engine of our livelihood, wellbeing and life on Earth as a whole (FAO, 2015). Soil degrading processes lead to environmental, social and economic problems, such as ecological erosion – the incremental deterioration or alteration of ecological communities and processes (Poulsen et al., 2013) – ecosystem de-stabilization (Loreau et al., 2003), higher risks for pathogen outbreaks (Jayaraman et al., 2021), reduced soil fertility, pollution of drinking water and water ecosystems (Adhikari and Hartemink, 2016; Rawat and Rawat, 1994; Delgado-Baquerizo et al., 2017), reduced water storage capacities (Shah et al., 2017) and reduced soil organic carbon (De Graaff et al., 2015).

Soil pollution usually leads to long-term damage that is difficult (e.g. diffuse pollution), costly, or in some cases impossible to remediate (Duarte et al., 2018). Thus, the R&I experts formulated a need for improved soil eco-toxicological knowledge on new contaminants, or pollutant mixtures, concrete contamination thresholds, potential links between soil and water pollution, as well as how emergent pollutants affect soil biota, their soil functions and finally ecosystems and human health. Preventing soil erosion and other forms of soil degradation remain hot topics with great potential for improvement (Borrelli et al., 2021; Poesen, 2018). According to the experts, we need to improve both our location specific and overarching (up to the global level) understanding of soil degradation and remediation dynamics. Further, they formulated a need for improved understanding of land abandonment effects, which may lead to soil degrading processes such as wildfires (Moreira et al., 2011), or increased soil erosion rates (Meusburger and Alewell, 2014). Particular efforts are also required in the area of soil and land remediation, e.g. developing threshold values, indicators, and combined methods (O'Brien et al., 2017). Regarding practitioners' perspectives, the experts mentioned the importance of researching economic aspects of soil protection and remediation measures. Similarly, cost-impact assessments of land and soil degradation would help to better understand losses as well as benefits of solution pathways.

### 3.1.2. Mitigate land take

Land take is the expansion of artificial surfaces over time (e.g. soil sealing, parks and gardens), usually at the expense of agricultural, forest, natural and semi-natural areas. It is an important challenge for SDG 11 '*Make cities and human settlements inclusive, safe, resilient and sustainable*'. Soil sealing is one of the most severe forms of land degradation as it is an almost irreversible process that leads to a nearly complete loss of soil functions (Prokop and Jobstmann, 2011). 51% of the total land-take in the EU in 2006 is due to sealed surfaces, for example through urbanization and infrastructures (Prokop and Jobstmann, 2011). The EU has set the target to achieve '*land degradation neutrality*' by 2030 (SDG 15.3.1) and '*no net land take*' by 2050 (EC, 2011).

The R&I experts emphasized the significance of policies for integration of soil health management in urban and infrastructure planning, promotion of combined use of space, or tools for land managers that ease the integration of soil health management. Economic instruments (e.g. taxes, subsidies) were mentioned to help reduce or stop land take. Further, it is important to ensure that decisions for urban and traffic planning are made by experts and guided by solid legal and regulatory frameworks. Finally, architectural awareness and innovations were proposed to contribute to sustainable solutions, as well as research that investigates potential relationships between soil health and healthy cities, since this may foster the transition towards sustainable soil management in urban areas.

### 3.1.3. Increase provision of ecosystem services & biodiversity

Increasing the supply of ecosystem services and biodiversity are important elements of SDG 15. While reduction and remediation of soil degradation has been discussed before, here the focus is on promoting soil ecosystem functions, services and biodiversity. Soils supply important ecosystem services such as provision of food or freshwater, regulating climate, floods and droughts, supporting nutrient cycles, and cultural activities such as education, or recreational values (Wall et al., 2012; Schirpke et al., 2017). Soil degradation and subsequent reduction of these ecosystem services leads to increasing costs and damages in the long-term, within soil management (e.g. increasing costs for fertilizers or irrigation in order to maintain agricultural productivity) and beyond (e.g. increasing costs for drinking water cleaning and supply, effects on human health) (Hagemann et al., 2019a; Williams et al., 2020).

The R&I experts stated the need for improved basic understanding of soil (micro-) biological and ecological processes (e.g. soil-borne disease dynamics and suppressive soils), soil biodiversity, functional diversity, and plant-soil-biome interactions. Further, they formulated a great need for research on soil multi-functionality as well as physico-chemical and ecological soil system stability in order to understand soil management impacts on diverse soil functions and to improve preservation or restoration efforts. According to the experts, focus should lie on holistic approaches that include both the landscape scale and specific situations (e.g. field scale). Trade-offs between ecosystem services need to be addressed as well and win-win situations should be pursued (Ndong et al., 2021). Payments for the maintenance of important ecosystem services by beneficiaries were proposed to compensate for additional costs of some practitioners. In order to justify such payments and to control their success, further research on quantification of diverse ecosystem services is necessary. Finally, healthy biodiverse soils should be incorporated in city planning (green-blue infrastructures) following the motto 'healthy soils lead to healthy cities'.

#### 3.1.4. Increase biomass production for food, fiber and energy

Facing a global increase in population combined with increasing degradation of soils and their functions, SDG 2 can be seen as a central goal for global development. Rockström and Sukhdev (2016) even postulated that all SDGs are either directly or indirectly connected to sustainable and healthy food. Given recent advances towards increased bioenergy production, SDG 7 '*Ensure access to affordable, reliable, sustainable and modern energy for all*' is also closely related to biomass production. Thus, a constantly increasing demand for biomass for food, feed, fiber and bioenergy has to be satisfied on reduced land area, with reduced external inputs, while negative impacts on soil and water quality, biodiversity and other ecosystem services have to be reversed.

According to the R&I experts, water and food security, as well as the development of sustainable production systems are very urgent R&I needs. A general consensus was that we need a 'beyond growth' thinking regarding biomass production, thus acknowledging the multi-functional character of soils in order to reconcile the antagonistic demands of maintaining soil health and fertility while meeting these diverse demands (Nathanail et al., 2018). Soil fertility, integrated soil and water management on the landscape level, and the integration with other soil functions need more focus in related R&I. A proposed pathway for reaching these urgent goals is to apply and promote more systemic R&I and management approaches, i.e. a more holistic view on the matter of biomass production with integration of other ecosystem services, aiming at the creation of win-win scenarios. The experts recommended agroecological approaches for developing nature-based situation tailored sustainable production systems that address biomass production, management, reduction of external inputs, soil degradation and remediation, ecosystem services, as well as socio-economic factors (Francis et al., 2003; Gliessman, 2015). Further details on the conservation and remediation of soil biodiversity were already discussed in the previous section.

#### 3.1.5. Mitigate and adapt to climate change

Arguably one of the biggest challenges of humanity is SDG 13 '*Take urgent action to combat climate change and its impacts*'. Land and soil management play a pivotal role in the regulation of the climate system, since soils are involved in the biogeochemical cycles of carbon and nitrogen (Muñoz and Zornoza, 2017). Depending on management, soil can be either a greenhouse gas source ($CO_2$, $CH_4$, $N_2O$) or a sink (soil organic carbon) (IPCC, 2019). The R&I experts emphasized the need to improve the basic understanding of the processes and dynamics behind greenhouse gas emissions and carbon storage in soils. The discussion included terms such as soil carbon storage capacity and management, soil carbon stabilization potential, anthropogenic impact on soils, resilient soils and climate-smart sustainable soil management. Further, the experts emphasized the importance of evaluating the effectiveness of policy instruments for increasing soil carbon stocks.

In addition, soils bear a great potential for adaptation to climate change. Soil and land management affects water regulation and can thus be used for flood control or reduction of drought effects through increasing the soil water storage capacity (Schneider et al., 2020; Whitfield, 2012). Most of such adaptation measures in agricultural soil management have synergistic effects on carbon sequestration and thus climate change mitigation (Hamidov et al., 2017). Therefore, the experts formulated a particular interest for relationships between soil carbon storage and other soil functions (e.g. biomass production). In urban areas, green infrastructures can prevent heat islands and significantly reduce peak temperatures during summer, which reduces heat related premature casualties (mainly senior citizens) and has positive effects on the livelihood in cities (Speak et al., 2020; Murage et al., 2020).

#### 3.1.6. Improve disaster control

Many forms of disaster control and prevention can be seen as ecosystem services and are thus as well a part of SDG 15. Floods, droughts, wildfires and landslides are major natural hazards that result from a complex interaction of natural, social, and economic factors. According to the R&I experts, development of prevention measures against disasters (fires, floods, landslides) is an important R&I need. The occurrence of floods and droughts is reinforced as a result of climate and land use changes (Hagemann et al., 2019b). Landslides occur on slopes, often caused by increased soil moisture after heavy rains and a related reduction in slope stability (Stolte et al., 2016). Further, vegetation changes due to land use change, or after weather extremes (e.g. removal due to storms, or droughts) can have negative impacts on slope stability (Löbmann et al., 2020). Thus, the R&I experts formulated a need to improve our understanding of the effects of land abandonment on soils and landscapes. Over the last decades, also the frequency of wildfires has increased all over Europe and worldwide (Abatzoglou et al., 2019). Larger areas of northern Europe have become prone to wildfires, due to more frequent and more intense droughts (Krikken et al., 2019). According to the R&I experts, we need to improve our understanding about effects of wildfire on soils. In Southern Europe, land abandonment induced vegetation change leads to increased wildfire risk (Moreira et al., 2011). Appropriate soil and land management helps to mitigate flood, drought, landslide and wildfire risks.

Despite the increasing importance of this topic with climate change, this societal challenge received rather little attention from the R&I experts. Reasons could be that this challenge was not emphasized enough during the workshop, or that according to the survey most of the included projects focused on agriculture, and only few focused on areas that are likely to be affected by disasters (e.g. urban areas near rivers/coasts, forests, mountain areas).

### 3.2. Knowledge types for sustainable soil and land management

#### 3.2.1. Living Labs and Lighthouses

According to the R&I experts, increased stakeholder engagement, multi-stakeholder, inter-disciplinary and multi-scale operational R&I are of crucial importance for overcoming conflicts of interest (trade-offs) and to allow informed decision making. Further, they emphasized that research methodologies should include elements for practical transition to ensure swift implication of R&I. Living Labs are spaces for participatory co-creation, co-innovation, trans-disciplinary and systemic research, thus including many elements of practical transition (Veerman et al., 2020). They develop systemic, location specific solutions for sustainable soil and land management that include land managers' motivations, socio-economic drivers, incentive mechanisms, business models, and local pedo-climatic conditions. Serving as centres for knowledge creation, dissemination and socio-cultural models, they seek to establish a successful sustainable development processes on a local to regional level. Lighthouses are defined as collaborations between Living Labs in order to additionally foster education, advertise best practise scenarios and promote practical implementation of R&I (Veerman et al., 2020; EC, 2021).

A prominent problem with current sustainable soil management knowledge is the fragmentation of our knowledge in research disciplines. Thus, the experts highlighted the role of Living Labs and Lighthouses for developing methodologies that allow interconnection of knowledge across disciplines in order to increase its usefulness for practical purposes. Such methodologies should include the integration of 'informal' knowledge, such as cultural knowledge and work experience. In summary, holistic, integrated, inter-disciplinary, location specific and participatory research approaches, as in Living Labs and Lighthouses, are vital elements for developing applicable sustainable soil and land management methods and to ensure their swift implementation (Nathanail et al., 2018). Therefore, the Horizon Europe Mission "A Soil Deal for Europe" includes the establishment of 100 Living Labs for sustainable soil and land use in the EU (EC, 2021), as a starting point for a changing research paradigm.

#### 3.2.2. Specific regions and sectors

Requirements for R&I in support of sustainable soil and land management are often specific to regional, or even local pedo-climatic and socio-economic conditions (Francis et al., 2003). Climate change adaptation in agriculture for instance requires increased drainage in high rainfall areas, while increased irrigation will be necessary in dry areas (EEA, 2019a). In order to implement fully sustainable soil and land management, it is important to include smaller geographic regions and pedo-climatic zones – such as coastal, mountain, karst, sub-arctic and arctic areas, or islands – in research efforts (e.g. through Living Labs) and to exchange this specific knowledge on a global level. Similarly, the R&I experts emphasized the necessity to develop situation tailored solutions that address location specific soil degrading aspects within their specific landscape context. Thus, the combination of location specific needs with an overarching process understanding (up to the global level) promotes location specific solutions as based on global knowledge exchange.

In addition, different soil use sectors play an important role, including niche markets. Agricultural areas for example are susceptible to soil erosion (Montgomery, 2012), while in urban areas soil sealing is a major concern (Prokop and Jobstmann, 2011). The diversity of pedo-climatic and socio-economic settings, as well as the diversity of sectors and thus specific needs may seem overwhelming. However, a strategy to cope with this diversity is to start with participatory research in some regions, within some sectors and to use these knowledge gains as a means for establishing vibrant knowledge exchange with and between other regions and sectors.

#### 3.2.3. Awareness, training and education

Raising awareness in a broader public, improving sustainable management knowledge and skills of practitioners, land managers, policy makers and the society as a whole are very important aspects for achieving more sustainable soil and land management (Rieckmann, 2018). Raising awareness is for example an 'added value' of citizen science, where people get engaged in research data collection, while learning about soil health and functions (e.g. the Tea Bag Index) (Sandén et al., 2020). The R&I experts emphasized the necessity of increasing efforts towards raising awareness of soil pollution, degradation and soil as an integrated part of landscape development over all sectors (agriculture, forestry, protected areas, urban areas, infrastructures and industrial soil use). A bilateral approach of push factors (demonstration of soil threats and their consequences) and pull factors (demonstration of benefits) was proposed for mobilizing people and to accelerate the transition towards sustainable soil and land management. In addition, it is important to evaluate the impact of awareness raising strategies, in order to improve success (Cameron et al., 2013).

Much research has been undertaken particularly in the social sciences and humanities domain about how to 'learn together, to manage together' (Kranz et al., 2005). However, while there are increasing numbers of scientific publications on education concepts for sustainable development, there is often a lack of empirical evidence of their effectiveness (Hallinger and Nguyen, 2020). One successful method of education for sustainable development is the holistic analysis of case studies (i.e. real life practice examples) in order to promote a broader view on interactions, synergies and tradeoffs between decision making, practices, the environment and socio-economic settings (Francis et al., 2011; Østergaard et al., 2010). The Agricultural Knowledge and Innovation System (AKIS) is an activity of the European Commission that improves means and skills to implement modern, stakeholder inclusive systems of joint learning and co-creation (Knierim et al., 2015). Future R&I should aim to exploit opportunities offered with digitized solutions to develop a Digital Agricultural Knowledge and Innovation System (DAKIS) alongside the AKIS.

#### 3.2.4. Data management, sensing and monitoring

With increasing amounts of collected data, including static data (basic soil information), monitoring data (time series) and research data (contextual), appropriate data management becomes more and more important. The FAIR principles (Findable, Accessible, Interoperable, Reusable) provide a solid basis for appropriate data management (Wilkinson et al., 2016). Despite great progress over the last years, the R&I experts formulated a need to further improve sharing of soil data and open access of scientific literature. Further, they formulated important research needs such as improving management responsive indicators for soil health, quality, degradation, soil functions and ecosystem services. Regular monitoring, mapping and reporting (e.g. every 5 to 10 years) are challenging areas of research that are crucial for detecting soil degradation or to identify and evaluate appropriate management techniques (Nathanail et al., 2018). Indicators, measurement protocols, models and data exchange need to be further developed, shared and standardized across countries (Bispo et al., 2017; Bouchez et al., 2016). Policies and strategies related to sustainable soil and land management require standardized assessment regarding their impacts (Paleari, 2017) on a wide range of societal challenges. The experts proposed subsidies that are linked to actual monitoring of the soil status as a means to improve data collection and thus local decision making. Further, they formulated a need for suitable success and failure indicators for policy or economic instruments, as well as for monitoring.

New technologies (e.g. portable scans, meta-barcoding, remote sensing, earth observation), as well as new ways of monitoring (e.g. citizen observations through participatory research actions) will provide more data for research, stakeholder and citizen interests (Bünemann et al., 2018; Rossiter et al., 2015; Wawer et al., 2019). Soil monitoring is facing a revolution, since the future national and EU monitoring campaigns will co-exist with participatory monitoring (e.g. Orgiazzi et al., 2018). Data coming from such diverse sources (e.g. laboratories, sensors, remote sensing, and citizen observations) require particular efforts for organization, storage and exchange in order to allow useful conclusions on soil health and soil functions.

#### 3.2.5. Assessment and modelling

With an increasingly complex understanding of the soil and land system, the need grows to assess alternative solutions for mitigating trade-offs and practical implications (Helming et al., 2018b). The R&I experts formulated a great need for more holistic and truly integrated research and assessment strategies that focus on multiple interactions between soils and the environment, balance and assess trade-offs, and overcome simplified approaches that are inadequate to match the complexity of soil and landscape realities. Such approaches require high levels of interdisciplinarity, interactions across sectors, inclusion of stakeholders and global collaboration. Currently, the development of integrated impact assessment tools is a rapidly growing R&I activity in the field of climate change, agriculture, soil and land management (Van Ittersum et al., 2008). Such tools can be used for dynamic assessments that promote forward looking decision-making (see Section 3.2.8 science based policy support). The experts proposed that modelling approaches should include impacts of soil and land related actions on the global climate, soil and water quality. Nonetheless, they emphasized that modelling is no replacement for broad scale and regular measurements in the field, among other reasons, because modelling often requires empirical research data both for design and validation. Combining both approaches can help to develop practical tools for stakeholders to understand and evaluate soil functions themselves. Existing agroecological principles and tools such as soft systems thinking (Checkland, 2000), problem analyses, and participatory research (Kranz et al., 2005; Leminen, 2013) are not limited to agricultural soil use and provide a solid basis for more holistic and solution oriented R&I, stakeholder engagement, and co-creation. The latter two combine the actual R&I with direct efforts towards adaptation and transition of scientific knowledge to practical implementation (Weith et al., 2020).

### 3.2.6. Technical, economic and social innovation

Innovations are seen here as specific, applicable solutions for sustainable soil and land management. Technical innovations can for example be novel technologies and techniques, or new applications of old technologies and techniques such as inclusion of pulses in crop rotations. Economic innovations may be the development of new markets, marketing schemes (e.g. community supported agriculture), or products (e.g. carbon trading, product certificates) (Devaux et al., 2018). Social innovations may include societal organization structures adapted to sustainable soil and land management (e.g. NGOs, or regional organizations). While we distinguish here between technical, economic and social innovation, we want to emphasize that there is a flowing transition between these categories with many innovations covering multiple of them.

Innovations for sustainable soil and land use are important drivers of a practical sustainable development. In particular the social and bio-economy sectors need more attention in order to increase competitiveness and overall success of sustainable management approaches (Nathanail et al., 2018). The R&I experts argued that payment schemes for ecosystem services (including carbon trading) are promising economic instruments that help mobilizing sustainable soil use practices. Similarly, circular economy approaches (including socio-economic needs), or green finance were mentioned to boost a sustainable development. The experts proclaimed a general lack of soil management technologies that encourage users towards soil protection, or that provide nature-based solutions for soil and land management. According to them, existing technologies are often underdeveloped, insufficiently tested, or lack proper marketing, competitiveness and legal support. They proposed further that sustainable innovation needs to be developed on a holistic level along the specific requirements for soil and land management in order to achieve a transition on the systems level. Thus technical, economic and social innovation should not be developed separately, but rather as practice oriented ‘innovation packages’, where different innovation elements efficiently support each other.

### 3.2.7. Institutions and governance

Governance aspects at multiple levels are of vital importance for sustainable soil and land use (Helming et al., 2018a). The R&I experts formulated a need for more effective and coherent policies with a view on long-term effects, including sustainable soil and land management guidelines and quantitative targets (e.g. the incorporation of soil health and biodiversity in city planning). A priority should lie on the removal of legislative barriers to the implementation of innovative sustainable technologies and practices (Veerman et al., 2020). Further, the experts proposed that subsidies should be linked to good practice and actual monitoring of the soil status, combined with penalties for causing damage (i.e. push and pull factors). More specifically, area based subsidies should be replaced in favor of payments for ecosystem services. While a transition towards ecosystem service based subsidies should be implemented shortly, more research is necessary on measurement and quantification of ecosystem services (see also Section 3.1.3). Private governance tools, such as certification services, crowd funding, or community supported agriculture are additional drivers for soil management decisions and have started to impact both the society as well as soil management towards more sustainable practices (Glasbergen and Schouten, 2015). Hence, R&I on the effects of current institutions and governance on sustainable soil and land management, as well as their improvement, are highly important for realizing practical implementation.

### 3.2.8. Science based policy support

Assessment tools and models for science based policy support (e.g. SAFA, RISE) (FAO, 2014; Häni et al., 2003) have been developed to support this impact assessment. In this context, agriculture and land management, alongside with climate action, proved to be front-running sectors for science-based policy support (Podhora et al., 2013). Development of forward-looking scenarios can be useful for creating coherent storylines that visualize and demonstrate future development options (Mitter et al., 2020) that can be used for stakeholder interaction, strategy and policy co-development. It is an important field of research to further improve the available tools and models for science based policy support and to provide outcomes of these tools and models in a format that is useful for policy making and management. Accordingly, its importance was well reflected in the great interest of the R&I experts. Specific R&I needs were formulated for developing pathways that ensure scientifically validated targets for policy making and for assessing positive and negative impacts of soil policies.

## 4. Discussion – systems knowledge for sustainable soil and land management

It is vital to understand and acknowledge for the multifunctional character of soils, the different needs of diverse stakeholders and the potential for conflicts between different stakeholder groups (Helming and Wiggering, 2013). In order to reach sustainable solutions, the variety of soil related societal needs must be addressed in symbiosis with the environment and moreover within its boundaries in order to minimize negative impacts (Gliessman, 2015). An integrative understanding of sustainable practices would enable contributions towards SDG 15 through improving awareness of soil functions, ecosystem services and soil biodiversity among stakeholders as well as facilitating the dialogue on ecosystem service values (Nathanail et al., 2018). The six identified societal challenges are highly interlinked and together describe a dynamic soil and land system (Fig. 3). Reducing and remediating soil erosion, pollution and degradation are important challenges for soil capacity building and thus help to increase provision of ecosystem services and biodiversity, since the latter largely depends on healthy and functional soils (Zhang et al., 2020; FAO and ITPS, 2015). Mitigation of land take is an important element of reducing soil degradation, for example through reducing soil sealing. In addition, it can directly increase the provision of ecosystem services through ecological improvement of green infrastructures (e.g. parks, gardens). Increasing provision of ecosystem services and biodiversity can help to increase biomass production, mitigate and adapt to climate change and to improve disaster control. Biomass production depends to a large extent on soil quality and health (FAO and ITPS, 2015), while many agricultural practices lead to soil degradation (Ramankutty et al., 2018). Climate change mitigation and adaption are important factors for reducing soil degradation in the long term through carbon sequestration, prevention of soil borne greenhouse gases (Muñoz and Zornoza, 2017; IPCC, 2019), as well as climate resilient adaptation of vegetation and management (FAO et al., 2018; EEA, 2019a). Disaster control is as well closely linked to soil quality, since both flood control and drought effects largely depend on soil water uptake and holding capacity (Whitfield, 2012; Schneider et al., 2020), which can be improved through soil quality management (Lal et al., 2018).

The knowledge types form an orientation framework that visualizes the diverse knowledge needs for sustainable soil and land management within and beyond each individual societal challenge (Fig. 4). Thus, while the societal challenges form the topic areas to be addressed, the knowledge types form a methodological bridge between topic areas, R&I and practical application within the broader socio-economic and political environment. Thus, our research showed that data management, sensing, monitoring,

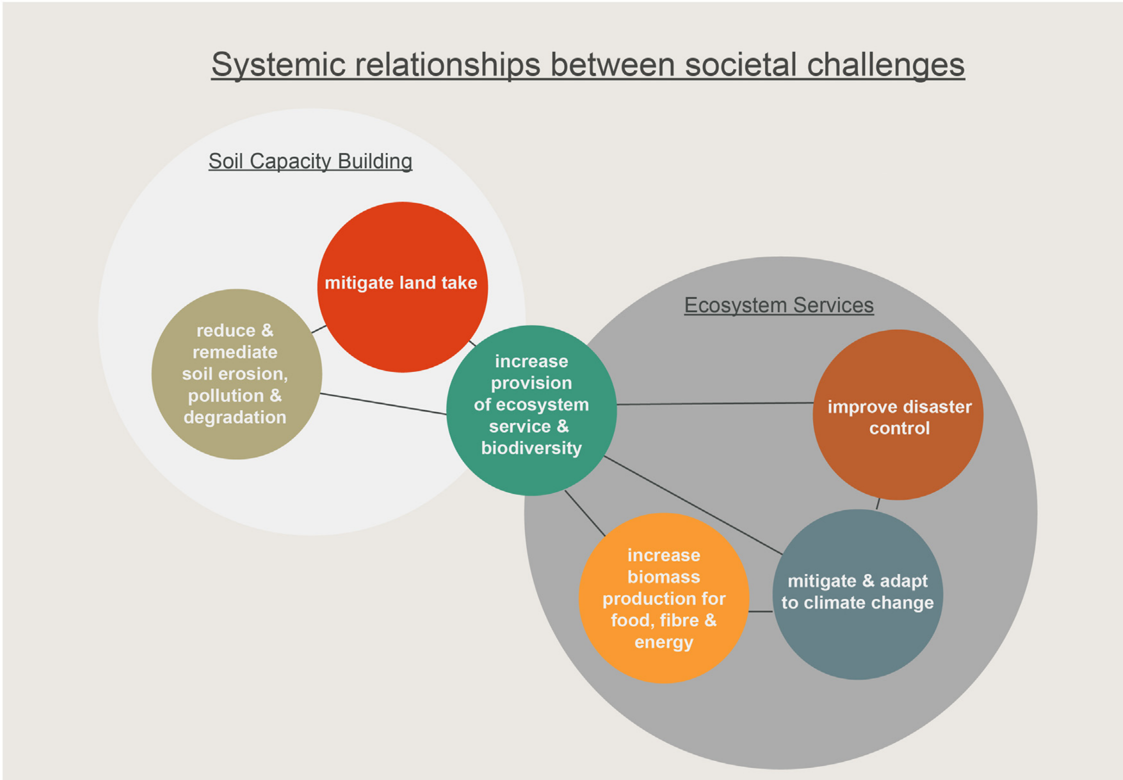


**Fig. 3.** Systemic relationships between societal challenges related to soil and land. A primary challenge is the protection and promotion of the soil capacity in order to increase the provision of soil ecosystem services.

assessment, modelling, innovation, institutions and governance are all important element that need to be addressed thoroughly for reaching sustainable soil and land management on a larger scale. Specific regions and sectors need to be addressed in order to ensure practicable adaptation of innovations to local conditions, requirements, actors' needs and wishes. Raising awareness, training and education ensure that actors and stakeholders realize the necessity for adaptation and it supplies them with knowledge and skills required to do so. Finally, within the whole research system, Living Labs and Lighthouses are special R&I infrastructures that have a strong focus on the latter two knowledge types, but are not limited to them. They closely interact and communicate with other R&I initiatives and form a permanent bridge between actors, stakeholders and diverse research communities. Finally, gained knowledge, experience and exchange with practitioners and stakeholders needs to be summarized to support targeted and promising policy initiatives in order to foster and guide goal leading decision making for sustainable soil and land management in the short and long term.

A successful R&I approach for sustainable soil and land management needs to maintain a programmatic overview of all related societal challenges and knowledge types, while it needs to balance tradeoffs together with stakeholders (people affected by soil management directly or indirectly) and actors (people engaged with soil management) in order to include their opinions, perspectives, problems, possibilities and realities (Helming et al., 2018b). These diverse elements are all important parts of an ongoing implementation process on a systemic level (Veerman et al., 2020). Respectively, the here presented systemic research framework forms a sound theoretical basis to stimulate systematic exchange, inter- and trans-disciplinary research (including natural science, social science and economics) for swift transition towards applied sustainable soil and land use. Being linked to the objectives and building blocks of the Horizon Europe Mission "*A Soil Deal for Europe*" it can help researchers to identify and address the diversity of soil and land related research needs that will be addressed during the upcoming Horizon Europe programme and beyond. Further, the knowledge types provide a comprehensive overview of the required elements for researching the goals of the Mission as well as for a more sustainable global society. Through this holistic approach, both in thematic and methodological terms, target knowledge and transformation knowledge are progressively combined through systems knowledge and understanding.

There are diverse application areas for the systemic research framework, for example for getting a wider overview of the soil and land system, research project planning and examination, development of systemic innovation that addresses multiple societal challenges, while minimizing negative impacts on others, or for exploring the wider systemic impacts of policies. Although the systemic research framework can be used in many different ways, we want to exemplify its applicability through proposing a simple three step workflow, based on the concept of (Hirsch-Hadorn et al., 2008), that can be applied to both epistemic and trans-disciplinary research and innovation (Fig. 5):

(1) System knowledge phase: A broad orientation, planning and research design phase, where a systemic view on the addressed problem situation (s) should be established (at best through stakeholder engagement) that directly or indirectly considers and evaluates all relevant societal challenges of the systemic research framework. A systemic overview helps to identify all important aspects related to the problems situation(s), its connections to other societal challenges, as well as synergies and trade-offs between them, which allows for a more systemic goal setting. Following, the knowledge types helps with choosing an adequate systemic methodology and related methods for solving the problem situation(s), while mitigating trade-offs and promoting positive synergies.
(2) Target knowledge phase: The performance of specific research and experiments aims at collection of data, evidence, or the development of innovation that supports sustainable soil and land management. The systemic overview should be further developed through field observations and interactions with actors and stakeholders. Thus, scientists should account

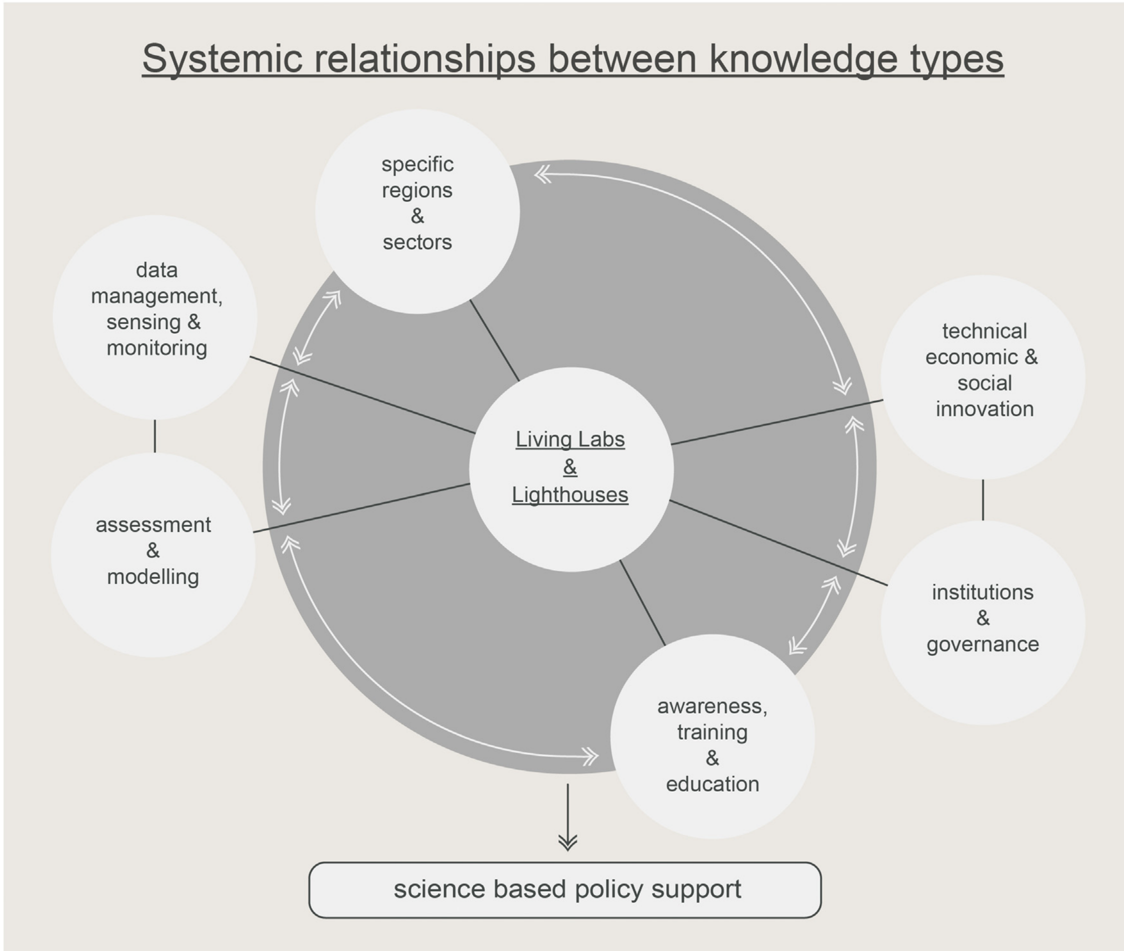


**Fig. 4.** Systemic relationships between knowledge types relevant to address societal challenges related to soil and land. Living Labs and Lighthouses play a central role for a transition towards sustainable soil and land management, due to their participatory and co-creational approach that applies or connects all other knowledge types.

for some flexibility in order to allow adaptations of experiment designs according to specific needs and intermediate results.

(3) Transformation knowledge phase: This outreach and implementation phase aims at presenting the research and innovation results within a systemic context in order to evaluate the knowledge gains and to allow researchers of diverse disciplines to properly interpret and work with them. In addition, outreach should aim to support actors and stakeholders with practical application of results and innovation as well as getting a systemic overview. Through a critical follow-up evaluation process, it is possible to identify impacts of the research, remaining knowledge gaps, missed opportunities and reasons either for success or failure.

Our systemic research framework for achieving sustainable soil and land management fosters more holistic and integrated research and innovation perspectives with a central focus on soil and land use concerns. While soil and land are directly or indirectly involved in reaching many SDGs (Bouma et al., 2019; Tóth et al., 2018), it is often difficult to draw system boundaries wide enough to sufficiently represent real life scenarios while scaling down complexity to feasible levels. Nonetheless, in order to reach a systemic and solution oriented perspective, we must not only focus on what we perceive as immediately 'useful' but rather include all practical implications (Ulrich, 2001). Setting feasible system boundaries is an exciting challenge for systems research that requires training and experience and needs to be addressed individually in specific contexts. However, we should always bear in mind that it is us who set these boundaries in order to improve workability and that they are thus not fully representative of reality (Checkland, 2000).

## 5. Conclusion

Through a participatory approach, we summarized the diverse, multifunctional, inter and transdisciplinary character of soil and land management and demonstrated the importance of addressing R&I activities with a holistic perspective. Considering all relevant knowledge types within the broader socio-political knowledge system helps with orienting individual R&I activities towards more targeted impact on the overarching societal goal of reaching sustainable soil and land management, as for example expressed in the Horizon Europe Mission "*A Soil Deal for Europe*". The identified elements as represented by six societal challenges and eight knowledge types are linked with each other through dynamic interactions. Soil and land management topics should thus not be regarded in isolation, but rather placed within a dynamic, location specific feedback system with bio-physical, economic, social and political elements. Our systemic research framework for sustainable soil and land management provides (I) a sound methodology for gaining a holistic overview of problem situations in order to pose goal leading research questions as embedded within a dynamic systems context, and (II) a holistic concept for targeted co-creational research performance that includes actual implication of R&I within practice, economy, society and politics. As particular R&I needs, we identified a lack of innovation and technology that is fit for practical application. Socio-economic interrelations with soil health and related policies currently represent the biggest bottleneck.

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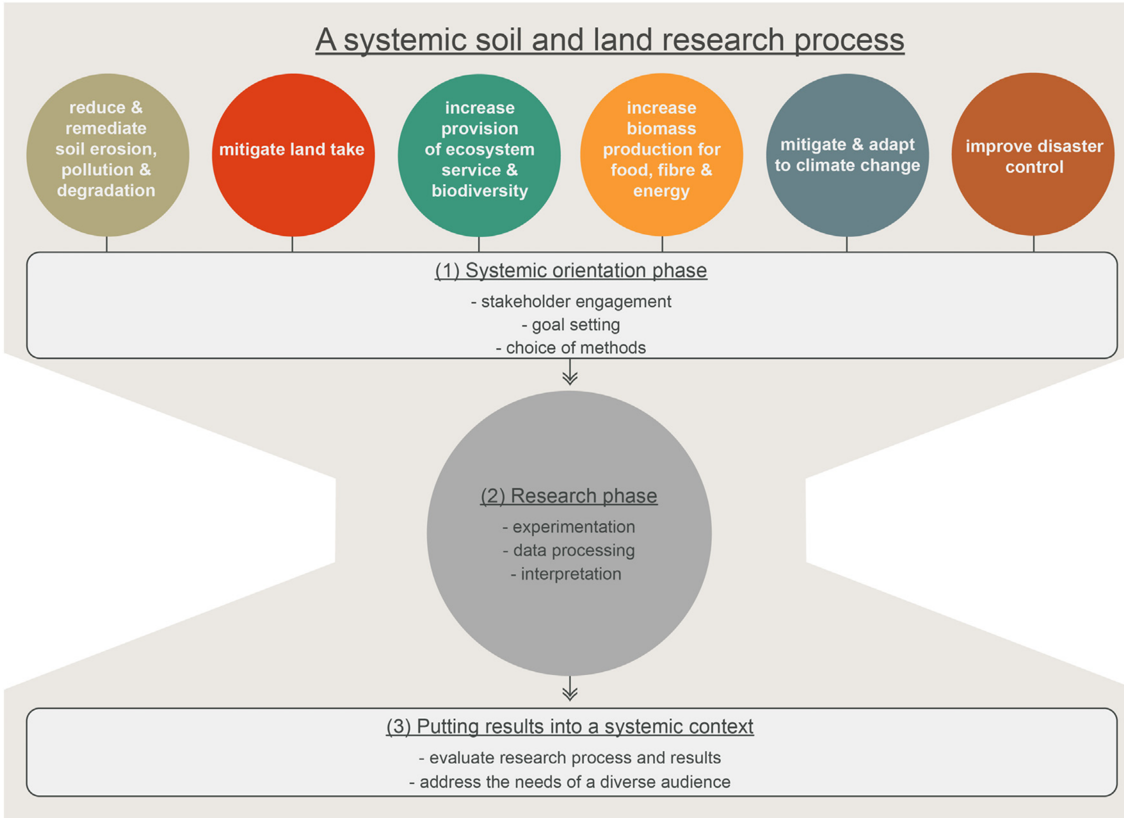


**Fig. 5.** Proposed workflow when using the systemic research framework for designing sustainable soil and land management R&I. During the orientation and research design phase, a systemic view is necessary that considers and evaluates all societal challenges and knowledge types in order to support holistic research designs. After performing the research, results need to be put back into a systemic context that allows a diverse audience to utilize them for their individual needs.

## Declaration of competing interest

The authors declare no known conflicts of interests or personal relationships that could have influenced the content reported in this paper.

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