S&T&I FOR 2050

Science, Technology and Innovation for Ecosystem Performance – Accelerating Sustainability Transitions

CASE STUDY: SOIL TO SOUL

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November 2022

Soil art. Credit: Talaandig Soil Paintings Facebook Page

1. OVERVIEW

This case study proposes three scenarios exploring human-soils relations. As sense-making devices, these scenarios discuss how different ontologies of soils shape different actions, be them soil management practices in agriculture contexts or Research and Innovation (R&I) practices.

The paper follows these steps:

- We provide a brief definition of soils and an overview of the threats and pressures affecting agricultural soils across Europe;
- We sketch out the three scenarios, differentiating them based on:
  - The social construction of (soil) nature, the notion of human-nature relationality; we discuss this in connection with three perspectives previously explored in the project: *protecting and restoring, co-shaping, immersing and caring;*
  - Implications for soil management practices and solutions, implications for research and innovation;
  - Relevant science, technology, and innovation (STI) drivers of change from a Dynamic Argumentative Delphi (DAD) consultation.

The resulting scenarios are summarized below:
(See Table 2 for a synthetic presentation of the scenarios informed by the three perspectives).

Eyes on the prize is tributary to a dichotomic view regarding the human sphere and the (soil) nature sphere. This can be articulated in different approaches: one urges a fundamental respect for and need to save nature by conservation or by controlling land use change; the other is concerned with the problems and possibilities resulting from the human alteration of soils and seeks salvation in technology-based interventions meant to mitigate human impacts.
Cultivating each other builds on the view that nature is intrinsically social, with socio–cultural and biophysical contexts continually co-evolving. In this scenario, agroecology and the soil management practices following its principles embrace the lessons that nature soils teach humans about the way they function. Therefore, we and the soils cultivate each other – they cultivate our understanding of their own dynamics, we cultivate them to nourish ourselves.

Full circle of life calls for new ontologies of soil nature that are able to accommodate not only individual species and their competing interests, but also environments and relations that undergird and enable life flourishing. In exploring the notion of relationality that includes humans and nonhumans, this scenario describes approaches to human–soil relationships that embed care and/or situated spirituality. These views open new forms of soil investigation and practice that acknowledge the biophysical agency of soil ecosystems, their sociocultural constitution, and the dynamic interactions between them. In this scenario, the microbial is taking centre stage, as a result of the growing recognition of the vital role soil organisms play in most soil functions.

2. WHAT ARE SOILS? HOW DO THEY SUPPORT LIFE?

The definition of soil depends on the perspective that generated it, so an engineer, a farmer or a diplomat may describe the meaning of 'soil' from different angles. From a soil science perspective, soil is the surface mineral and/or organic layer of the earth that has experienced some degree of physical, biological, and chemical weathering. In brief, soil is a material composed of several ingredients which interact in a myriad of ways — approximately half air and water, 45% minerals and 5% organic matter. Most of that 5% is plant, animal, and microbial residues in various states of decomposition, and only 10% is life, but that 10% contains some of the greatest biodiversity in the biosphere (Dasgupta, 2021).

The skin of the earth is essential for all life-sustaining processes on our planet. A healthy soil is a magnificent reservoir of life to the extent that 25% of animal species on Earth live underground, while 40% of organisms in terrestrial ecosystems are associated with soil at some point during their lifecycles (FAO, 2020). They provide habitats that support thousands of different species of fungi, bacteria, and invertebrates, which then work in combination to drive the Earth's carbon, nitrogen and water cycles. An estimated 12,000 miles of hyphae, or fungal filaments, are found beneath every square meter of healthy soil. Moreover, soil is rich in the nutrients that plants need to survive and provides the physical structure for the roots and stems that helps hold plants up. Soils are also critical to human survival: after food production, the most important function of soils is the replenishment and purification of groundwater, which supplies our drinking water. Considering this, a simple, straightforward understanding of soil health refers to its ability to support all life, human and non-human.

It is argued, however, that the dominant research paradigm for soil health emphasizes instrumental values - the unilateral flow of benefits from soil to humans to improve human well-being (e.g. nutrient cycling, plant available water, pollutant degradation), neglecting and marginalizing non-instrumental values of soil health (Friedrichsen et al., 2021). Soil health has value to society beyond instrumental value in the form of relational values that emerge, for example, from farmers' narratives about their motivations and incentives. These relational values are the benefits derived from a caring relationship with soil by an individual or a community. Moreover, intrinsic values exist outside of the value placed on nature by humans.

Thus, the act of defining the baseline of what a potentially healthy soil looks like (in any specific region) is a valued act. In the following sections exploring three perspectives on soil ecosystems, there will be ample opportunity to investigate the plurality of values associated with soil health. But for now, it's important to underscore the fact that healthy soils are supporting life — all life.

3. DRIVERS OF SOIL HEALTH - THREATS/PRESSURES AFFECTING SOILS

Soils are threatened all over Europe and globally because of a range of human activities. It is estimated that 60-70% of soils in the EU are in an unhealthy state (EC, 2021). The typology of degradation and its intensity is directly influenced by the anthropogenic activities carried on respective soils, such as deforestation, mining, extractive farming practices or over-exploitation, excessive grazing, excessive ploughing, urban expansion etc. This means that different soils (respectively different land cover types – arable land, pastures, forests, artificial surfaces) 'suffer' in different ways.

We focus in this synthesis section on soil degradation that is specific to agriculture land. While soil is threatened by a number of human activities, agriculture is a particular culprit, given the scale and depth of soil degradation it causes: The main share of land in Europe is used by agriculture land, with grass- and cropland together making up 39 % of land cover in the EU. The pressures and threats for all terrestrial species, habitats and ecosystems most frequently reported by Member States are associated with agriculture (EEA, 2015 in SOER, 2020). Various pressures from agriculture can have combined impacts on ecosystems and have cumulative effects. For example, in relation to soil, pesticide use can reduce soil biodiversity, irrigation can lead to salinization, soil compaction resulting from heavy machinery use can reduce growth and resilience of crops as well as carbon formation and water retention capacity, and the risk of soil erosion is also increased through compaction as well as through increased land parcel size. The share of GHG emissions from agriculture is currently around 10 % and while overall emissions have declined from 1990, in the last few years they have increased from both livestock and soils (SOER, 2020).

The following examples regarding types of degradation (physical, chemical, biological) reflect how widespread and diverse are the threats and pressures across EU agricultural soils.

Soil contamination

Soil contamination can be diffuse and widespread or intense and localized (contaminated sites). Sources of contaminants include the residues of plant protection products, mineral fertilizers, biosolids (some composts, manures, and sewage sludges). Depending on soil properties and their concentrations, contaminants in soil may enter the food chain, threaten human health and be toxic to soil-dwelling organisms (FAO and ITPS, 2017). Substances that are not readily degradable will eventually leach into surface and groundwaters or be dispersed by wind erosion (Silva et al., 2018 in SOER, 2020).

- *There may be as many as* ***2.8 million contaminated sites in the EU, but only 24 % of the sites are inventoried.***
- *Cadmium — mainly originating from mineral phosphorus fertilizers — accumulates in 45 % of agricultural soils, mainly in southern Europe where leaching rates are low due to a low precipitation surplus****. In 21% of agricultural soils, the cadmium concentration in the topsoil exceeds the limit for groundwater, 1.0 mg/m3 (used for drinking water)*** *(SOER, 2020)*
- *While copper is an essential micronutrient, excess levels in soils are a source of concern. Copper has been widely used as a fungicide spray, especially in vineyards and orchards.* ***Evidence shows elevated copper levels in the soils in the olive and wine-producing regions of the Mediterranean*** *(Ballabio et al., 2018 in SOER 2020).*
- *There is also increasing concern about* ***the residence and accumulation of pesticide residues and their metabolites in agricultural soils, and their potential release mechanisms****, for example due to acidification and wind erosion (Silva et al., 2018 in SOER 2020). Exceedance of critical loads for nitrogen is linked to reduced plant species richness in a broad range of European ecosystems*
- *Excessive nutrient inputs to soils through fertilizers, which leads to acidification and eutrophication.* ***For approximately 65-75 % of the EU-27 agricultural soils, nitrogen inputs*** *through fertilizers, manure, biosolids and nitrogen-fixing crops* ***exceed critical values*** *beyond which eutrophication can be expected (SOER, 2020)*

Soil organic matter decline

Soil organic matter (SOM) is essentially derived from residual plant and animal material, transformed (humified) by microbes and decomposed under the influence of temperature, moisture, and ambient soil conditions. Soil organic matter plays a major role in maintaining soil functions because of its influence on soil structure and stability, water retention and soil biodiversity, and because it is a source of plant nutrients. The primary constituent of SOM is soil organic carbon (SOC) (FAO, 2015).

- ***Some 45 percent of soils in Europe have low or very low organic matter content*** *(0–2 percent organic carbon). This is particularly evident in the soils of many southern European countries, but is also the case in parts of France, the United Kingdom, Germany, Norway, and Belgium. A key driver is the conversion of woodland and grassland to arable crops (FAO, 2015).*
- *Different forms of soil degradation (SOC loss, tillage, pollution, compaction, and erosion) negatively impact the habitat available for soil organisms****. In all regions across Europe, the species richness***

of earthworms, springtails and mites has been negatively affected by increased intensity of land use (Tsiafouli et al., 2015).

- *In a recent assessment covering the period 2009-2015,* ***carbon in mineral cropland soils in the EU-28 was shown to be broadly stable or slightly declining*** *(albeit at much lower levels compared with other land cover categories), while* ***carbon in grasslands showed slight increases*** *(Hiederer, 2018).*
- *The largest amounts of SOC are found in organic soils such as peat. Peatlands are currently under threat from unsustainable practices such as drainage, clearance for agriculture, fires, climate change and extraction (FAO, 2015).* ***13-36 % of the current soil carbon stock in European peatlands might be lost by the end of this century*** *(Gobin et al., 2011).*

Soil erosion

Erosion describes the loss of soil by water and by wind and harvest losses (i.e., soil adhering to harvested crops). Apart from the loss of productivity and soil function, erosion of agricultural soils is also critical because of their proximity to surface waters, leading to the transfer of soil material and pollutants into water systems.

- *The estimated mean soil erosion rate by water is about 2.46 t/ha per year in the EU (which is 1.6 times higher than the average rate of soil formation) (Panagos et al., 2015). Accordingly,* ***12.7 % of Europe's land area is affected by moderate to high erosion*** *(soil loss rates > 5 t/ha per year).*

Soil compaction

Soil compaction is the result of mechanical stress caused by the passage of agricultural machinery and livestock. The consequences are increased soil density, a degradation of soil structure and reduced porosity (especially macroporosity). This causes increased resistance against root penetration and also negatively affects soil organisms, as their presence depends on sufficiently sized pores (Schjønning et al., 2015 in SOER, 2020). Compaction is known to be a significant pre-cursor of erosion. Soil compaction may lower crop yields by 2.5-15 %, but it also contributes to waterlogging during precipitation events, which not only reduces the accessibility of fields to machinery but also negatively affects run-off, discharge rate and flooding events (Brus & van den Akker, 2018 in SOER, 2020).

- ***About 23 % of soils in the EU-28 are estimated to have critically high densities in their subsoils****, indicating compaction (Schjønning et al., 2015 in SOER, 2020).*

Salinisation and sodification

While naturally saline soils exist in certain parts of Europe (e.g., in Spain, Hungary, Greece and Bulgaria), the main concern is the increase in salt content in soils resulting from human interventions such as inappropriate irrigation practices/ use of salt-rich irrigation water.

- *Artificially induced salinization is affecting significant parts of Sicily and the Ebro Valley in Spain and more locally in other parts of Italy, Hungary, Greece, Portugal, France, and Slovakia (FAO, 2015).*

Theme	**Past trends and outlook**	
	Past trends (10-15 years)	Outlook to 2030
Urbanisation and land use by agriculture and forestry	Deteriorating trends dominate	Deteriorating developments dominate
Soil condition	Deteriorating trends dominate	Deteriorating developments dominate

Fig 1. Assessment of past trends and outlook regarding land use and soils (SOER, 2020).
Note: The figure refers to agriculture land use but not exclusively.

4. SCENARIOS ON HUMAN-SOILS RELATIONS

The scenarios sketched in the following sections are informed by a previous exploration on different perspectives on the notion of ‘ecosystems flourishing’ (Warnke et al., 2021), summarized in Table 1.

The three perspectives reflect different values, ideas, and norms regarding the environment. They bring to light various ‘battles of intimate representations’ of human-nature relationships, echoing the debates around the social construction of nature, and implicitly of the soil. The way agency is discussed differs in the three perspectives. Also, they contain different narratives around soil-humans – of reparation, of partnership, of kinship – that shape the imaginings of the present and the future. The ethos permeating these narratives varies from self-interest followed by guilt to mutual support to reciprocal care.

The vocabulary accompanying the three perspectives borrows conceptualizations from various, (sometimes) overlapping discourse communities, among which ecological knowledge systems, social-ecological systems, socio-technical systems, ecological economics, environmental economics, economics of services, critical geography, biocultural traditions, feminist ethics and politics of care.

These different understandings can lead to very different management and policy devices, which is to say they have an influence on the society's concrete actions on nature – specifically, in this case, on soils. This does not mean these perspectives are completely mutually exclusive, nor that the practices derived from them are always completely incompatible. But there are considerable qualitative differences in the visions that underpin them which prove consequential in how soil management is performed, now and on the long run.

While land use in Europe is diverse, the discussions in the three perspectives focus on soils that are relevant for and impacted by agriculture. As detailed in the section regarding threats on soils, agriculture carries an extraordinary force to affect soils, both in intensity and in scale.

Table 2 below is meant to highlight the specificities of each perspective, the critical differences that give them substance. Further on, each of the three perspectives is declined in scenarios, which in turn contain sections on:

- Social construction of nature
- Implications for soil management practices and solutions and for science & innovation
- Relevant STI drivers of change from a Dynamic Argumentative Delphi (DAD) consultation*

**The Dynamic Argumentative Delphi (DAD) consultation was carried out between December 2021 and March 2022, and engaged hundreds of experts from around the world in an argument-based exploration regarding the contribution of science, technology and innovation (STI) to the capability of ecosystems to flourish from now to 2050. In elaborating this case study, we studied the DAD survey results referring to soils, under the different thematic domains assessed in the survey (Dragomir et. al., 2022).*

Table 1: Overview of perspectives on ecosystem flourishing

Perspectives regarding the capacity of ecosystem to flourish

Warnke et al. (2021) provide a conceptual framework presenting three possible perspectives on ecosystems flourishing emerging from a review of recently proposed concepts. The three perspectives differ not only in the types of indicators they propose to assess ecosystems status but also in the very notion of ecosystems and their proposed interaction with the human sphere.

Perspective	Notion of ecosystems	Motivation to promote ecosystem flourishing	Proposed attitude towards ecosystems flourishing	Type of indicator us to assess ecosyste flourishing
P1 Protecting and restoring ecosystems	Distinctive nature sphere interacting with the human	Costs and benefits of (in-)action re-	Manage the impact of human activities to	Distinctive measures environmental pressu

	sphere (natural capital)	garding limiting effects on the environment	reach a desired target. *Fix existing problems.*	on the state of the environment e.g., pollinator diversity, soil organic carbon etc.
P2 Co-shaping socio-ecological systems	Complex adaptive socio-ecological systems with no clear boundaries	Steer system dynamics towards long term survival	Move specific socio-ecological systems towards more beneficial dynamics. *Design, experiment and scale up solutions.*	System resilience (learning capacity), institutions of polycentric governance
P3 Caring within hybrid collectives	Pluriverse of hybrid entities with agency emerging out of relations to each other	No other choice for humans, ethics of care	Negotiate with other inhabitants of critical zones to allow all to flourish on their own terms. *Adapt to nature and its diversity*.	Number of flourishing of life projects, pressure on other collectives

Table 2. Overview of scenarios on human-soils relations, informed by the three perspectives

	Using, protecting and restoring	*Co-shaping socio-ecological systems*	*Caring within hybrid collectives*
Scenario title	**Eyes on the prize**	**Cultivating each other**	**Full circle of life: womb and tomb**
Key descriptors on the social construction of soil nature	- Soil as provider of goods and services, mainly valuable when benefitting people - Human interventions on soil seen as alternating between destruction/degradation and reparation/conservation	- Soils and humans are moulding each other continuously - Humans work in partnership with the dynamics of soils towards resilience/adaptiveness of the socio-ecological system	- Human-soil communing emerging in relational entanglements where not one element holds 'the key' - Who animates whom is an open question when the soil community is seen as the ongoing creativity of a myriad of creatures - New ecological cultures of care for the non-human world
Types of knowledge	-Science is mainly technoscience -Knowledge has value if it can facilitate appropriation and management of resources.	- Knowledge builds on a continuous feedback loop with nature - Embedding indigenous or traditional local knowledge and experience -Technoscience may be involved, but less myopic to the interactions among constituents and across scale, time	-The re-emergence of other languages, sensibilities, and practices of relating to soils, beyond the dominance of natural science framings -New technoscientific imaginaries of soil aliveness -Science participates to an ecological culture around soils - Acknowledgement of spirituality not as defiant of scientific practice, but as contributor to its enrichment
Implications: Soil management practices	-Specific solutions to particular impacts ('half-baked sustainability')	- Ecosystem based adaptation - Nature based solutions - Agroecology and its associated practices – agroforestry, regenerative agriculture, permaculture etc	- Agroecology and its associated practices – agroforestry, regenerative agriculture, permaculture etc - The practice of 'collaboration' with microbes and other soil biota - Soil management practices 'infused' by indigenous knowledge and spirituality
Implications: Science/R&I policy	- More affordable and accessible innovative technologies aimed at reducing the various types of soil degradation	- Living labs and lighthouses to co-create, test and pioneer innovations for soil health at local level - Sets of sustainable soil management practices in line with agroecological principles, adapted to the wide variability of soil ecosystems and types - Research on narratives of personal and collective identity as intimately connected to soils; their role in mobilizing farmers/stakeholders towards sustainable agriculture practices	- Investigating soil microbiome materialities and agencies - Soil 'microbiopolitics' (contestations around the appropriate ways of relating to microbial entities) as a crucial arena for future research - Greater engagement with soil sense-abilities building on emerging technologies/techniques: eDNA metabarcoding; technologies aimed at non-invasive, non-destructive, 'seeing' and 'hearing': e.g., visualisation methods, bioacoustics

			-The realms of imagination and spirituality receiving attention in emerging soil care research.
Limitations	- Perpetuation of a separation between the natural and human sphere that cannot support ecosystem flourishing on the long run - Inability to radically challenge ('stretch and transform') current regimes with their power concentrations	- If solely the responsibility of farmers, agroecology and the associated sustainable agriculture practices cannot strive against the economic pressures in current contexts - The success of these practices is supported/hindered by the narratives of farmers and other stakeholders regarding their identity	- Challenges in translating into practices and norms the understanding of human-soil relationships as matters of care, marked by spirituality - Life-affirming intentions can still be overruled by the logic of the greater economic game

4.1. Eyes on the prize

P1 Using, (abusing) then protecting and restoring ecosystems

This perspective builds on the view that there is a dichotomy between humans and nature. This might lead to a '*nature-first'* approach which urges a fundamental respect for and need to save nature, or get back to nature, or might generate a '*people and environment'* approach, which is concerned with the problems and possibilities resulting from the human alteration of natural resources, environments, and organisms (Castree, 2001). The former leads to land use change controlling, restoration, and conservation. The latter to technology-based interventions meant to mitigate human impacts. Such soil technologies bring their own valuable contributions but, instead of transforming our intimate representations and our connection with soil nature, risk generating new ways of commodifying and appropriating it.

Social construction of nature in Perspective 1

This perspective has its roots in the natural sciences, which have emphasized an ontological separation between humans and nature since at least the European Enlightenment. In the 'pristine myth' (Denevan, 1992) paradigm generated by natural sciences, human societies are recent destroyers or, at least, disturbers and troublemakers in a mostly pristine natural world. The notion of an untouched/pristine Earth became part of the DNA of early conservationists thinking of the nineteenth century.

This separation between the human sphere and the natural sphere persisted, albeit becoming more nuanced, and informed the concept of ecosystem services that appeared in the late seventies of the twentieth century, as a useful metaphor to draw public attention to the degradation of ecosystems caused by human activities. The notion then gradually acquired the status of a scientific concept, with the release of the Millennium Ecosystem Assessment (MEA) in 2005 and further gained traction in scientific, policy and political arenas dealing with environmental issues. The working definition of this concept is straightforward - ecosystem services are, essentially, the benefits humans derive from nature, directly and indirectly. Proponents of the concept emphasized the role of the health of ecosystems on service provision. As for people and societies, they are, above all, the beneficiaries or users of these services. When authors examine the influence of societies on the environment – in our case on the soil, it is either in terms of pressure on ecosystems and degradation of services (e.g., pollution, resource overexploitation) or in terms of preservation and protection of ecosystems (Barnaud & Antona, 2014).

Authors of MEA proposed four types of ecosystem services, a classification that while debated, is still frequently adopted: *provisioning services* (products obtained from ecosystems), *regulating services* (benefits obtained from regulation of ecosystem processes), *supporting services* (ecosystem functions underlying other ecosystem services); *cultural services* (non-material benefits people obtain from ecosystems). The Mission Board Soil Health and Food follow the same terminology when discussing ecosystem services derived from soils, such as: producing adequate quantities of nutritious and safe food, feed, fibre and other biomass for industries; storing and purifying water, regulating flows, recharging aquifers, and reducing the impact of droughts and floods thereby helping adaptation to climate change; capturing carbon from the atmosphere and reducing emission of greenhouse gases from soils, thereby contributing to climate mitigation; nutrient cycling supporting crop productivity and reducing contamination; preserving and protecting biodiversity by preserving habitats both above and within the soil; supporting the quality of our landscapes and greening of our towns and cities.

The success of this concept meant that diverse audiences increasingly acknowledged the concrete, tangible, and measurable existence of services supplied by soils to humanity, and it drew attention to the necessity to protect and better understand them. Bearing in mind there are critiques of the notion of ecosystem services, including soil ecosystem services, the notion marks the importance gained by the view of humanity as dependent on soils as non-human nature. Other concepts are meant to smoothen the human-centric accent of ecosystem services: the term '*ecological solidarity'* is a concept that refers to the same idea of human dependence on ecosystems, but without the economic connotation of the word service. In the same vein, bodies like the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) adopted the concept '*nature's contribution to people'* (NCP).

Credit: *Cross section through fertile soils* by Romul Nutiu

Implications of perspective 1 for soil management and for R&I

The view that societies are degraders of nature that needs to be protected in biosphere reserves, habitat areas, and wilderness zones trades on the distinction between a predatory humanity and a fast-disappearing nonhuman world (Castree, 2001). Following this vision, a response to degraded land/soils would be the prohibition of agricultural activities within a protected area that provides some services of particularly high value (Barnaud & Antona, 2014). Controlling land use is relevant, for example, when discussing the relevance of soils for climate change mitigation, noting that wetlands, grasslands, and forests contain a large portion of the carbon stored in soils (preceded by soils of permafrost regions, which store the largest amount of soil carbon on the planet: 25%). When wetlands are converted into arable land or (short) rotation plantations, or if peat is extracted, large amounts of greenhouse gases are released. The same holds for the conversion of grasslands and forests. Thus, controlling land use change holds by far the greatest potential when it comes to global soil carbon stocks – much greater than agricultural and soil management practices (Beste & Lorentz, 2022).
In brief, land use change controlling, restoration and conservation are means to prevent human-induced degradation. It's an obvious way of keeping humans - the abusers, the destroyers - at bay.
Moreover, the 'people and environment' approach generates a tension mainly between our demand for soil's provisioning services, on one hand, and our need for regulating, maintenance, and cultural services, on the other hand. This is further complicated by the fact that some final services (services and goods directly appreciated by humans) might come at the cost of the intermediate ecosystem services (some of which remain mostly invisible, although they contribute to the final services) (Birkhofer et. al, 2015).

The ample debates revolving around the ways in which these tensions can be reduced are, in essence, aligned with the thinking that soils are providing services, benefits, goods to us humans, we just need to be careful regarding the extent and intensity of our demands from soils. To call it bluntly, eyes are (still) on the prize –

our food (with focus on yield, nutritional quality), our clean water, our clothes, our medicines, our landscapes provided by the generous soils.

In this context, soil science together with soil management practices contribute to a narrative of technofixism, oftentimes primed to generate isolated solutions for specific impacts. The atmosphere of urgency and anxiety about imminent resource exhaustion seems to give impetus to 'breakthroughs' and 'disruptive innovations'. Plenty of these techno-solutions are performing the complicated balancing act of keeping the aim of agricultural yield/gain while promoting sustainable soil care. The tension has to do with two complex goals: saving the world from starvation and saving the soils from ourselves. Puig de la Bellacasa (2015) adds an interesting dimension to this by noting that the tension between production and sustainability at the heart of soil science involves a clash of temporalities: between acknowledging soil as a slowly renewable entity and the accelerated 'technological fix' touted by techno-optimists. The paced renewal of soils' fertile capacities (including by leaving parts of the land at times in a fallow state) is incompatible with the general atmosphere of emergency. The author adds that this renders caring for soils into mere control of the object of our care (as opposed to care as an inherent relationality, a notion we discuss in perspective 3).

As described in the section on drivers of soil health, there are multiple agriculture-induced types of soil degradation, one of which being the contamination of soils following the excessive nutrient inputs to soils through fertilizers. Against the problem of leaking, for example, site- and crop-specific nutrient management has proven an efficient way to reduce emissions associated with the use of nitrogen fertilizers while still getting crops the nutrients they need to succeed. Moreover, the use of nanoscale active ingredients, features like controlled release, and targeted delivery of nanofertilizers are being developed as efforts to promote sustainable agriculture (Toksha et al., 2021).

With regards to pesticides development, the trend of global pesticide development has been gradually shifting from chemical pesticides to biological pesticides, GM crops, seeds, RNAi pesticides, and abiotic stress control agents. Of those, biopesticides are gaining popularity as lower-environmental-impact alternatives to conventional synthetic pesticides. Some predictions posit that biopesticides will equal synthetic (chemical) pesticides in terms of market size by the late 2040s or early 2050s (Umetsu & Shirai, 2020).

However, it's worth scrutinizing these innovations against the backdrop of transition theory, which discusses different niche-derived transition pathways, distinguishing between innovations that '*fit and conform*' to the established socio-technical regime from the ones that '*stretch and transform*' it (Smith & Raven, 2012). In brief, 'fit and conform' pathways focus on innovations which offer competitiveness for the dominant incumbent players. For instance, input-substitution solutions such as biopesticides, climate-resilient seeds, and other bio-based products are increasingly commoditized and patented by agro-chemical companies that normally sell agro-chemical inputs; thus, continuing farmers' dependence on large-scale monoculture systems and external-input markets (Larsen, 2021).

Advanced technologies like sensors, artificial intelligence, and robotics are also relevant in this scenario - they are being proposed as means to increase food production efficiency while reducing resource use and/or prevent soil degradation. The argument put forward is that combining digital tools (such as GPS, sensors and data modelling software) with automated technologies (e.g., smart tractors, drones and robots) will help farmers be more precise with inputs (i.e. seeds, water, fertilizers and pesticides), avoid soil compaction and minimize erosion while increasing their knowledge of agro-ecological conditions (including weather and landscape interactions and soil and plant health). Smart robots may even be better suited for intercropping, or growing multiple crops in the same field, a sustainable farm practice that encourages soil health and decreases pests but is costly and inefficient to do with current technologies.

However, there are multiple challenges associated with deploying robots in agriculture, from the considerable cost of design and engineering increasingly better ones to the large energy consumption involved with smart systems, to the resources necessary in building them, that implies draining the soil through the mining of minerals, like copper and lithium, to the issue of waste disposal (Miller, 2021). From the labor perspective, opinions greatly diverge on the impact of agricultural tech, with some voices suggesting that it can positively contribute to growth in rural communities by creating new workplace opportunities, and others anticipating the development of a high-skill/low-skilled bifurcated labour market and the exploitation of marginalized and racialized workers by landowners, governments, and corporations (Rotz et al., 2019). Outside the agricultural sector, agritech may aggravate exploitative practices in mineral mining, and may even exacerbate a global underclass of workers programming AI algorithms in unfair working conditions (Miller, 2021).

STI drivers of change from the Delphi study that are relevant for perspective 1:

- *Mitigation of human impacts on nature (including soil) through conservation and restoration*: Planning for nature reserves on a planetary scale; Land restoration; Conservation, restoration and proper management of existing natural carbon sink habitats (grasslands, forests); Ecological corridors;
- *Agritech reconfigured as big data science;*
- *Automated technologies* to identify, monitor and eradicate invasive alien species in terrestrial ecosystems
- *New fertilizers and solutions for reducing hydrogen and phosphorus leakage*: Improving yield predictions and estimations of nutrient availability to adjust the fertilization rates; Fertilize on plant demand assessed by sensor/ model/ RS advancements; Development of phosphorus-use efficient plants; Nanofertilizers; Nano chelated iron fertilizers; Controlled release fertilizers;
- *Increase water use efficiency*: Precision irrigation; Non-soil-disturbing weed control systems;
- *New pest control methods*: Nanobiotechnology for pest control; Plants with durable resistance to biotic stress by gene editing; Targeted molecular interventions such as dsRNA; RNAi genetic sprays; Insect growth regulators; Targeted molecular interventions such as dsRNA.

4.2. Cultivating each other

P2 Co-shaping socio-ecological systems

This perspective is marking a clear departure from the assumed distinction between the human and the nature sphere. In fact, it builds on the view that nature is intrinsically social, with socio–cultural and biophysical contexts continually co-evolving. The constant, profound, shape-shifting entanglement between soils and social systems is the most natural thing there can be. In this scenario, agroecology and the soil management practices associated to its principles embrace the lessons that nature soils teach humans about the way they function. Therefore, we and the soils cultivate each other – they cultivate our understanding of their own dynamics, we cultivate them to nourish ourselves.

Social construction of nature in Perspective 2

This perspective is grounded in the understanding that the human sphere and the natural sphere – in this case the soil ecosystems – are far from being separated. Land and soil use can be thought of as a tapestry of ever-evolving anthropoecosystems with higher or lower degrees of transformation – more or less human-shaped, or ‘domesticated’ environments (Stephens et al., 2020).

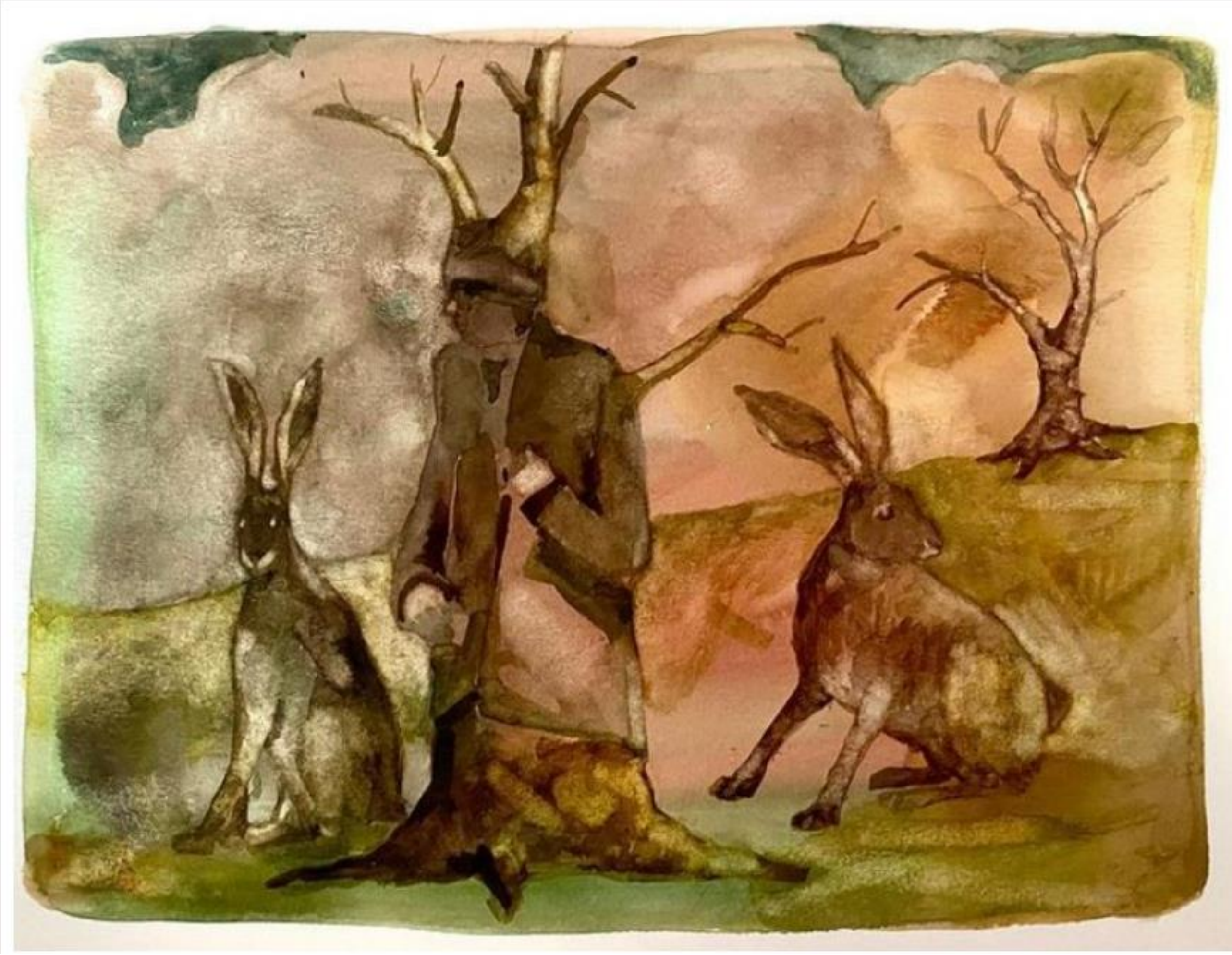
The social construction of nature is scrutinized. Scholars in critical geography point out that ‘nature’ and ‘wilderness’ exists only in people's imagination because, concretely, the impact of humans' actions can be found everywhere, in any ecosystem. "Nature has never been simply 'natural' [...] Rather, it is intrinsically social", “the physical characteristics of nature are contingent upon social practices” (Castree, 2001).

The ancient soil *terra preta* – dark earth – of the Amazon is an illuminating example. While much of the soil in the Amazon rainforest is very nutrient poor, muck like a thin red dust, there are patches, often along rivers, where extraordinarily fertile, deep, dark black soil can be found—rich with calcium, phosphorus, and potassium. The extent and spread of *terra preta* have contributed to the revelation that the Amazon is not a pristine wilderness that was only ever home to a few scattered peoples. It shows that pre-Columbus, agrarian communities “fundamentally changed their home, collaborating with the nonhuman world to create complex new ecologies that included them” (Marris, 2019).

Coevolution theory supports this perspective, as it addresses how different entities or relationships mutually influence each other’s evolution. Coevolution is a process of open and non-deterministic change between culture, practices and biophysical environments that mutually influence each other’s evolution (Schill et al., 2019 in Haider et al., 2021). This line of thinking rejects the notion of ecological and social/cultural systems as separable entities, proposing instead a focus on processes and dynamic relationships that constitute a social–

ecological whole (Weisz et al., 2011). For example, agricultural practices can be understood as coevolving with the landscape and the soil, as the practice shapes the soil, and the soil shapes the practice. The soil-related practices of sowing and harvesting, together with storing and preparation of food are examples of social–ecological practices that have coevolved with landscapes over millennia in response to changing environmental and social contexts and needs.

Soil culture theory accentuates even more the human-soil interdependencies and posits that different types of soil distributed throughout the world have fostered different cultures, for example: rice paddy soil cultures, loess cultures, oasis soil cultures, grassland soil cultures, coral limestone soil cultures, laterite soil cultures, red-yellow soil cultures, brown forest soil cultures, podsol cultures (Fujiwara,1990 in Minami, 2009).
Finally, some streams of literature around the notion of ecosystem services also incorporate this thinking by discussing the role of people in the provision of ecosystem services, through the intended or unintended positive impact of their activities on ecosystems. Examples from agricultural practices refer to the influence of livestock grazing on biodiversity in grasslands, the impact of agricultural land-use on pollination or the aesthetic value of agricultural landscapes (Barnaud & Antona, 2014).



Credit: *The Glen* by Travis Shilling

Implications of perspective 2 for soil management and for R&I

In this perspective, soil management requires an integrated strategy that goes beyond isolated solutions for specific impacts. It emphasizes the interlinkage between the diversity, quality, vitality and health of soil, plants, animals, and people, following the understanding that human-soil is a dynamic relationship that constitute a social–ecological whole. As such, human management of soils is based on a continuous feedback loop with nature – farmers/soil managers are educated about current evidence on how soil ecosystems function, how they interrelate with other ecosystems (water, air), and are aware of the fact that the complex web of interactions – spatial and temporal – cannot be forcefully simplified. These practices require time for positive effects to materialize. While these practices do not imply a return to ancestral forms of agriculture, some are rooted in indigenous or traditional local knowledge and experience (Beste & Lorentz, 2022).

Agroecology, a holistic approach to agriculture, follows principles of ecology coupled with food and nutrition security, food sovereignty and food justice. Agroecology promotes a functional biodiversity and nutrient cycling and the principle of working with nature. It seeks to maximize the autonomy of farmers, emphasizing and drawing on farmers' knowledge and local resources, while challenging power structures for social and ecological transformation. It is important to underline that rather than imposing a prescriptive framework, agroecology has been lauded for articulating a set of flexible values and principles that allow bespoke implementation in specific territorial contexts, reflecting their social, political, and biocultural circumstances. This contrasts with top-down attempts to propose a generalized agroecology which uproots it from the place-based, social, and political moorings which define agroecology. (For example, institutions such as the FAO and the French government have taken up agroecology in their policy discourse, but they have been criticized for reframing agroecology in narrow technocratic terms) (Anderson et al., 2019). As agroecology is knowledge-intensive rather than resource-intensive, boosting knowledge has been claimed as a critical component of any strategy to promote agroecology.

Moreover, while theories of transformative learning often focus on individual learning processes, there are important contributions preoccupied with collective learning processes, with analyses focusing on: the conception of territory as a subject of learning processes (McCune & Sánchez, 2019), the process of local dynamization (López-García et al., 2019), agroecology learning networks as an integral part of the process of social movement building (Anderson et al., 2019).

Agroecology is gaining increasing interest from European farmers, civil society organizations, and policy experts, who underscore the fact that advancing an alternative to the established agri-food regime means reclaiming decision-making power and processes from powerful lobbies and corporate interests. The European Commission openly endorsed agroecology as a preferred, albeit non-exclusive, approach to agriculture in the *Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system*. There are voices suggesting that its success depends on its prioritization by the Horizon Europe mission on soil health and food, supported by Common Agricultural Policy (CAP) reforms (Larsen, 2021).

Agroforestry, organic farming, regenerative agriculture, permaculture are all practices that uphold agroecology principles, promoted as pathways towards sustainable farming practices in Europe, given their potential to empower small-scale farmers, enhance agroecosystem resilience, and promote nature-based solutions, all within a broader perspective on food security and sovereignty.

In agroforestry, a version of agroecology, perennial plants such as trees and shrubs are specifically combined with cropping systems and / or livestock (agrosilvopastoral systems). There is a substantial amount of research in Europe dealing with ecological aspects of agroforestry, such as carbon sequestration, root length and root interaction of trees and crop, biodiversity (Ivezic et al., 2021). For example, Project Drawdown proposes Multistrata Agroforestry (a perennial cropping system that features layers of carbon-sequestering vegetation, with one or more layers of crops growing in the shade of taller trees) as a solution at the centre of land-based climate solutions, noting that although its adoption potential is modest, it can have a disproportionately high mitigation impact because it can offer the high sequestration rates of afforestation and forest restoration while providing food.
Regarding the effect of trees on annual crop yields, there is little consensus. A recent study concludes that there is a scarcity of relevant information on yields in agroforestry system under European growing conditions (Ivezic et al., 2021).

Organic farming follows the principles of agroecology, but it's particular in that it requires certification. Furthermore, the objectives of regenerative agriculture are similar to those of organic farming and agroecology; it focuses on the improvement of soils, water cycles, vegetation and productivity through agriculture, emphasizing soil building and humus enrichment. Project Drawdown defines the Regenerative Annual Cropping solution as any annual cropping system (excluding rice production) that includes at least four of the following six regenerative practices: compost application, cover crops, crop rotation, green manures, no-till or reduced tillage, and/or organic production. These practices sequester carbon in soils and reduce emissions at modest rates but have wide adoption potential and thus impressive mitigation potential.

Permaculture also avoids mineral fertilizers and synthetic pesticides and works with diversity. In addition, it specifies a particular arrangement of crops and primarily uses perennial varieties. Most permaculture cultivation practices are rooted in traditional indigenous knowledge. Permaculture promotes high resilience under changing external influences and in particular extreme weather events. Its practice involves farming based on natural cycles and ecosystems (Beste & Lorentz, 2022).

While the agricultural practices described above involve farmers managing soils in a more convivial way, the impact of their efforts can be curbed or hindered by the socioeconomic contexts in which human actors are embedded – for example through the necessity of staying financially afloat.

It's worth noting that the potential to mobilize more farmers/communities to engage with sustainable agricultural practices (this can also be referred to as 'sustainability transition') also depends on the narratives of the farmers in relation to their land/landscape, they personal and collective identities being closely connected to the lands/soils where they live and work. For example, a recent study on the crucial role of landscape in the dairy sector in a rural area in the Netherlands (the Green Heart) discusses, among others, two prototypical narratives amongst the farmers: 'Stewards', and 'Artisanal entrepreneurs'. Stewards are typically very concerned with the biodiversity on their land and in their soil. They aim to restore the health of the whole ecosystem. On the other hand, artisanal entrepreneurs perceive themselves as custodians and producers of the landscape; they may adopt punctual techno-fixes but resist a more radical change of the regional landscape. There is still ample room for research regarding place identity in different European landscapes. Understanding the role played by landscape (and more granularly land and soil) in identity formation and reformation means better, more intimate understanding of what drives farmers in running their farms the way they do. Transitioning towards sustainable agriculture practices might rely heavily on the capacity to navigate and/or alter these attachments.

This scenario calls for interdisciplinary and transdisciplinary approaches in soil-related research and innovation; current mechanisms reflecting such approaches are the Living Labs and the Light Houses. Living Labs are places to experiment on the ground, established on territorial, landscape, or regional scale. They represent user-centred, real-world research environments in which not only science, business and organizations jointly carry out research and development, but also the users themselves take an active role within the innovation processes. Lighthouses are single sites, like farms or parks, where scientifically proven good practices and solutions are demonstrated. They are places for mutual exchange and peer-to-peer learning. Good practices are further tested under real life conditions to inspire other practitioners to move towards sustainable soil and land management (EC, 2022). A recent project called *Soil Mission Support* created an interactive map of existing initiatives in Europe that qualify, to different degrees, as Living Labs or Light Houses; out of them over one hundred are related to agriculture.

STI drivers of change from the Delphi study that are relevant for perspective 2:

- *Sustainable agricultural practices*: Agroecology, Pastoralism, Permaculture; Agroforestry; Appropriate tillage regimes; Intercropping; Optimized crops for mixed cropping; Strip cropping; Agricultural production systems to sustain ecological restoration (e.g., native seed farming);
- *Soil amendments*: Composting, Biochar, better integration of waste streams in fertilization schedules; Symbiotic nitrogen-fixing bacteria; Free-living nitrogen-fixing cyanobacteria; Phosphorus-solubilizing biofertilizers; Potassium-solubilizing microbes; Nitrogen-supplying mycorrhizae.

4.3. Full circle of life

P3 Immersing and caring

This perspective is even more radical in challenging and undoing the separation between nature and humanity. It calls for new ontologies of soil nature that are able to accommodate not only of individual species and their competing interests, but also of environments, and relations that undergird and enable life flourishing. It posits that soils are not merely lively materials: soils are both *lively* and *alive*. Troubling these distinctions between 'alive' and 'lively' means integrating thinking about living beings and material flows in more-than-human and materialist ethics (Krzywoszynska, 2019). Soil materiality is "connected and dynamic, less of an isolatable entity than continuous, relational movement" (Lyons, 2014 in Krzywoszynska, 2019).

In the scenario accompanying this perspective, the microbial is taking centre stage, as a result of the growing recognition of the vital role soil organisms play in most soil functions. Also, this scenario explores the notion of relationality that includes humans and nonhumans, describing approaches of human–soil relationships that embed care and/or situated spirituality. This could contribute to new forms of soil investigation and practice that acknowledge the biophysical agency of soil ecosystems, their sociocultural constitution, and the dynamic interactions between those factors.

"Our relation to land is deep; our roots are deep in the soil, simultaneously culturally and materially. Caring for and about soils is thus not external. Caring for soils is about caring for particular ways of being human." (Krzywoszynska & Marchesi, 2020)

Social construction of (soil) nature in Perspective 3

Taking a step back: Representations of soils in languages, religions, ethnopedology

A very brief investigation on the etymology of words for soil, and the place of soil in philosophy and religion helps set the stage for this perspective. For example, the ancient Chinese definition of the two-character (*tu* and *rang*) compound for 'soil' refer to soil in both its natural state (*tu* is strictly *that which fosters life*) and in its agricultural state (*rang*). Japanese *tsuchi* did not signify soil in general but was a name that called forth something spiritual concealed in the ground, the embryonic source of life. Multiple systems of thought and religions are intimately connected to soils: the Greek theory of the four elements (earth, water, air, and fire), the Greek myth of creation (Chaos, Gaia, Tartarus and Eros), the Brahmin Veda of ancient India (Samagana songs and Mother Earth), the prostrations of Tibetan Buddhism (unification of the mother of the land and spirit of the land) (Minami, 2010). The Andean deity Pachamama, 'world-mother' is a source of the four Quechua cosmological principles of water, earth, sun and moon, the rights of whom are now protected by Bolivian law (Krzywoszynska & Marchesi, 2020). The Christian Bible (Old Testament) says "And the lord God formed man of the dust of the ground and breathed into his nostrils the breath of life; and man became a living soul". The term *Homo* - human, comes from *humus* - meaning soil. The defining quality of humanity is that after spending their lifetimes working the land, they will return to the land, "for dust thou art, and unto dust shalt thou return" (Genesis 3:17) (Minami, 2010).

Ethnopedology studies show the diversity of ways in which soils are brought into social relations. For Colombian smallholders in the Amazon, growing crops involves cultivating a place-specific sensibility to the taste, smell, and touch of the earth (Krzywoszynska & Marchesi, 2020). In Celtic cultures, the spirits of the soil (*dei terreni*) represent spirits of agriculture that make grains yield well and cows give much milk. Australian Aborigines feel that harming the land is harming themselves. In Switzerland, spirits called gnomes, resembling tiny old men, were believed to dwell in the soil. Soil-related spirits are also common across Asia, such as the Ainu *kamui*, the Ryukyu *nirai kanaii*, China's *tiandi*, Thailand's *phi*, and the Philippines' *anito* (Minami, 2010). In Western, more recent times, Austrian farmers feel that soil qualities are a manifestation of their own moral rectitude, while in Switzerland soil aesthetics are essential in farmers' perceptions and communication of good soil management practice (Krzywoszynska & Marchesi, 2020).

Relational ethics, care and spirituality

A growing body of research and practice is approaching human–soil relationships as matters of care. Caring, the practical and ethical commitment to ensuring the well-being of others, is a promising way of conceptualizing and acting on the interdependence of human and non-human lives (Puig de la Bellacasa, 2017). Relational ethics scholars have discussed the ways in which attentiveness generates (through affective moments such as enchantment, curiosity, or disgust) relational ethics and a response-ability towards non-humans (Pigott, 2021). Krzywoszynska (2019) posits that in order for soils to flourish, there needs to be an extensive 'care network' in place - as caregivers seek to better attend to the needs of the primary object of their care, they extend care to other entities on whom the wellbeing of the primary object of care depends. One of the author's case studies illustrates that attending to soil biota as a way of caring for the farm business has led to a certain reconfiguration of both the farm businesses and land use practices. She stresses, however, that the farmer's power to act is limited. Krzywoszynska concludes that only when caring is more than the obligation of particular individuals (farmers) and becomes a systemic project (engaging all the participants in the agri-food system), the radical potential of attentiveness can be fulfilled.

The shift in awareness about soil and human-soil relationships is also marked by questions of spirit. In this context, spirit is not strictly related to a certain body or referring to religion, but rather "any embodied or disembodied non-human agency that is experienced, interacted with or is otherwise socially consequential" (Szerszynski, 2017).

Puig de la Bellacasa's work (2019) has situated spirituality as an important terrain of inquiry in relation to human–soil relations, extending notions of care to more-than-human worlds. She uses spirit to refer to distributed non-human agency, a sense of enlivenment or animateness which is mysterious precisely because soil aliveness is not explicable by mechanical principles alone. The author proposes affectively charged motifs of intimate entanglement with soil aliveness – 'biological wonder', 'interdependent livingness', 'sensual enlivenments', 'life as regeneration and animateness' – that are briefly described below:

- *Biological wonder* – refers to efforts, across the technoscientific spectrum, directed at revealing hidden soils, at making them visible/noticeable. Science participates to an ecological culture around soils, and scientists are also touched, not only by environmental concerns and public pressures, but by a wave of renewed affection for soils that invokes science to support better care.
- *Teaming with life – interdependent living* - Soil as a medium that connects different forms of life that depend on it for everyday subsistence. An everydayness by which humans and non-humans are engaged in intimate entanglements of ecological care. Care as a material doing of everyday maintenance and repair. A particular angle is found in the scientific 'foodweb' concept of soil that focuses on 'collaborating' with microbes and other soil biota.
- *Sensual enlivenment - affectionate encounters* with soils involve intimate, sensorial engagements with soil substance through smell, taste, touch etc. Such sensual intimacy is also something deemed both pleasurable and necessary by passionate soil scientists and farmers.
- *Regeneration – afterlife as shape-shifting* - Soil as the exquisite recycler of matter, the great digester, Mother Earth's gut, microbes turning plant and animal remains into nourishment, making rebirthing possible through elemental re-circulation.
- Our own death means the returning of our matter to the soil. Degradation of bodies can be seen as a lively collaboration between bodies and soils. Recently, in Washington state in the USA, a company called Recompose hopes to be the first provider of post-mortem 'natural organic reduction', allowing people to reconnect with the cycles of nature. A hexagonal container with a carefully balanced ratio of wood chips, straw, and alfalfa helps decompose a human body within a month, after which the body and its accompanying vegetation are transformed into a cubic yard of soil (Marris, 2019).

Pigott (2021) reflects on the spiritual practice of biodynamics (originated in Steiner's agriculture work proposed as 'spiritual science') which, in her view, can engender an attentiveness to soil as something that is agential, energetic, and alive. The mysterious, spiritual elements of this practice encourage an attentiveness to the possibility that humans have limited control; that there are 'things' that exceed us individually and collectively, and thus to the possibility that soil 'cares' for us, too. This strengthens notions of the soil care network as multidirectional and interdependent, with care as a totality of living and non-living entities that enable life and mutually nourish one another (Lyons, 2014 in Pigott, 2021). Biodynamics prompts an attunement to more-than-human worlds, which are more ephemeral and unmeasurable, such as the energetic qualities of air, water, plants, and animals.

Moreover, in spiritual practices, imagination and faith play a crucial role, in addition to hands-on practices. Sharing of imaginings and narratives may prove more important in generating care than the knowledge gained through direct bodily encounters, as it prompts a geographical imagination of interdependence that surpasses our individual spheres of experience (Pitt, 2018 in Pigott 2021). The realms of imagination and faith are therefore deserving of further attention in emerging soil care research.

Credit: *FarmerPlanet by Travis Schilling*

Credit: Organic by Levi van Veluw

Implications of perspective 3 for soil management and for R&I

Across a science-policy-public spectrum, efforts directed at revealing hidden soils, at making them visible, come with a message: knowing soils better could enable better care (Krzywoszynska, 2020a). Science is in the position to reveal the mysterious alterity of soil. New and thoroughly technoscientific imaginaries of soil aliveness are being developed (Puig de la Bellacasa, 2019). For example, the Global Soil Biodiversity Atlas, published by the EU funded European Soil Data Centre presents striking images of soil's living creatures and tells us: 'Soil is Alive!... Organisms living in the soil are many, amazing, smart, important, and unique. Soil biodiversity is full of incredible stories.' (Orgiazzi et al., 2016).

Advances in visualization methods that are non-invasive and non-destructive – for example X-ray computed tomography technologies that study soil's interactions around plant roots – contribute to revealing the unseen soils (Mairhofer et al., 2014 in Bellacasa, 2019). Moreover, the field of soil bioacoustics (also referred to as biotremology or soil ecoacoustics) engages a growing number of biologists in capturing underground noises that may open a window into a complex and cryptic world. Every soil organism produces its own soundtrack. By distinguishing these sounds, soil acoustics stands to shed light on some hitherto unanswerable questions such as: When do plant roots grow? How are plants making use of sound to help their survival? Are predators – birds, rodents - listening to the underground sounds? Might fungi be able to register sounds coming from micropredators? What intended signals between soil (micro)organisms are revealed by subterranean vibrations? (Eberle, 2022).

Genetic research, particularly the technique of (eDNA) metabarcoding provides new opportunities for large-scale soil biodiversity studies, oftentimes proving to be more effective than other methods and less costly, making it ideal for a variety of further applications in ecology, including interactions between the macro- and micro-biome. Some relevant examples: Metabarcoding of soil and sediment has been applied to the characterization of eukaryotic communities and the assessment of their response to environmental changes. In the case of invertebrate-species, metabarcoding proved more sensitive to habitat differences than traditional surveys. Studies also looked at root associated fungal communities by using metabarcoding, with findings suggesting that fungal communities are tightly linked to plant communities. The ability of metabarcoding to describe diversity in bulk arthropod samples was also tested, revealing that that metabarcoding was able to identify 91% of the arthropods as well as detect microbes associated with the arthropods. The methods can be also used to reconstruct ancient habitats, analyse animal diets, detect invasive species, or study the interaction of plants and pollinators (Ruppert et al., 2019).

The technologies presented above, and their associated technoscientific imaginaries of soil aliveness, are sure to contribute to a better understanding - seeing, hearing, feeling - of soil life, galvanizing an ethos of care.

In addition, farming practices that respect the principles of agroecology (described in more detail under perspective 2), such as permaculture, regenerative agriculture etc, are carried with respect towards soils' functional biodiversity and natural nutrient cycling; in this sense they embed a specific care about the aliveness of soils. Taking the notion of soil liveness even further, some alternative growers' movements have embraced the concept of 'foodweb', a concept in soil science that describes the exceptionally complex interactions between soil species that allow the circulation of nutrients and energy. Under this notion, soils are web-like, interdependent, which means that altering or removing any one element can destroy them. These notions emphasize a living world below, teeming with life, and fragility. Analysing foodweb models through the lenses of care involves considering "the dependency of the (human) carer from, not so much soil's produce or 'service', but from an inherent relationality that renders soils capable to 'take care' of a number of vital life processes" (Puig de la Bellacasa, 2015). Foodweb based soil care may imply, for example, composting in order to giving back to the soils what we take from them.

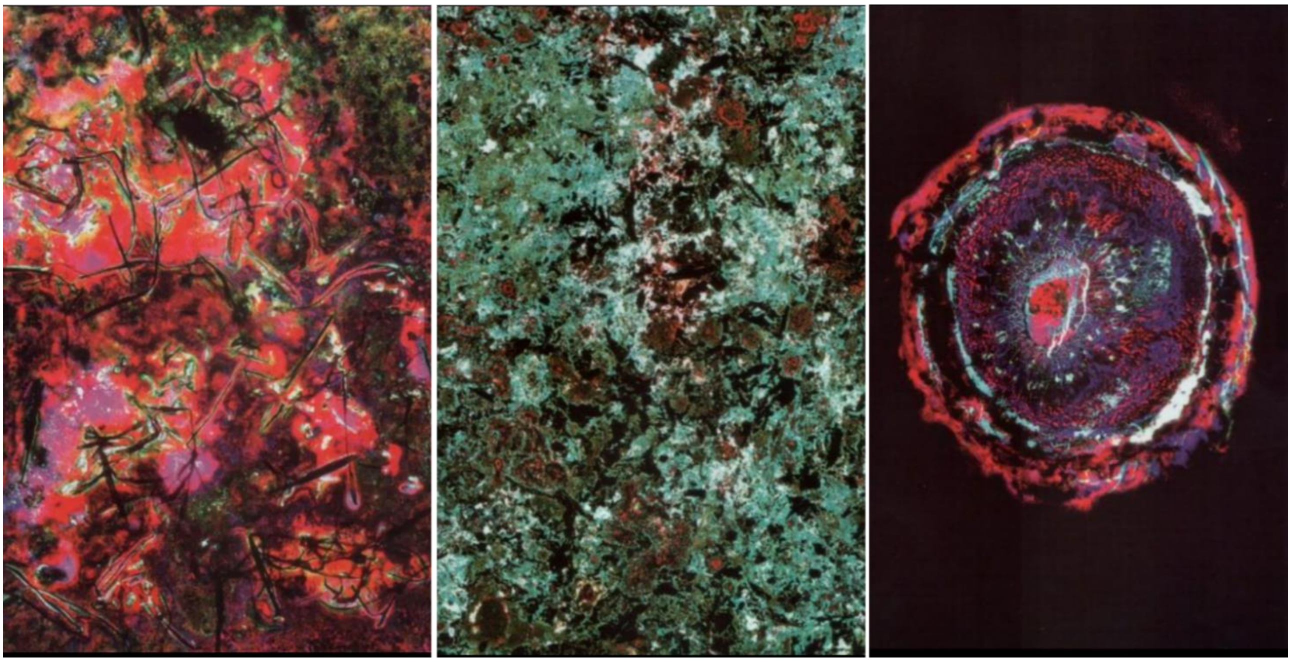
With regards to agroecology, Toledo (2022) suggests that while it has contributed extensively to the practice and epistemology (science) of sustainable agriculture, it has only by exception engaged with the ontological/spiritual components of farming. He argues that "recognizing and integrating spirituality into agroecological practice would reinforce agroecology as a socially and environmentally liberating activity" (ibid). Toledo also underscores that "spiritual beings" (actors who are profoundly engaged with the ontological component of their worldview) share a common attribute which is immensely valuable in an agricultural context: humility. "Human beings not only acknowledge that they are powerless, imperfect, limited, and finite, but also recognize their own mistakes […] humility can thus be a key attribute of the practice of agroecology and contrasts with the idea of "ruling over nature" more common to agroindustrial practices". Humility and a sense of limited power in the face of natural processes is something that modern movements in agroecology, regenerative agriculture, or other sustainable agriculture movements can draw from indigenous wisdom and practices.

There are strong reasons to believe that knowing soils better could enable *different forms of* care, but whether or not this always enables *better* care is not clear. Parts of Krzywoszynska's research with UK farmers clearly suggests that this is not necessarily the case. Soil may continue to be perceived as valuable because of its ability to produce agricultural commodities. These commodities are bought, sold, stored, speculated upon, and soil biota are cared-for so that they will render soil more productive. The current system, even amongst regenerative farmers, creates at best probiotic relations of care between farmers and soil life (Krzywoszynska, 2020a) in which life-affirming intentions are still overruled by the logic of the greater economic game. Given one of the main features of regenerative agriculture – the preoccupation with the fight against climate change – a particularly interesting aspect is the widespread interest in soil-based carbon credits. Krzywoszynska (2020a) asserts that soils themselves are not being commodified; the commodity is instead the products of their 'labour'. Trade of soil-based carbon credits could represent a more direct form of objectification and financialization of soil life than does the trade of agricultural commodities.

STI drivers of change from the Delphi study that are relevant for perspective 3:

- *Achieving human-nature coexistence*: Peacefully challenging the idea of endless growth; From goods and services to gifts and gratitude; Explore shifts from human-nature coexistence to human-nature relations;

- *Sustainable agricultural practices*: Agroecology, Pastoralism, Permaculture; Agroforestry; Appropriate tillage regimes; Intercropping; Optimize crops for mixed cropping; Strip cropping; Agricultural production systems to sustain ecological restoration (e.g. native seed farming);
- *Soil amendments*: Composting, Biochar, better integration of waste streams in fertilization schedules; Symbiotic nitrogen-fixing bacteria; Free-living nitrogen-fixing cyanobacteria; Phosphorus-solubilizing biofertilizers; Potassium-solubilizing microbes; Nitrogen-supplying mycorrhizae;
- *Pest control methods*: Phage bio-control of bacterial pathogens
- *Bridging the gap in soil biodiversity data*; use of genetics to reveal cryptic species
- *Protection of soil biota & Improvement of soil by microorganisms*: e.g. Retention of soil organic matter; Promoting beneficial plant-microbe interactions; Microbial prospection; Calibration of soil parameters favouring desirable microbiomes; Extended use of mycorrhizae; Recycling biomass; Extended use of plant growth promoting bacteria; Leveraging the potential of microbiomes for organic-waste circularization into food/feed; Extremophiles for agriculture;
- *Study and analysis of the soundscape* as an indicator of the state of health of terrestrial environments.



Soil art: do Daro Montag's Bioglyphs: a series of eco-cosmic prints resulting from soil organisms consuming buried photographic film (collage made from images from the artist's gallery)

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