Make all soils healthy again!

WUR Student challenge

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I. Preliminary discussion

1. Why do we need a soil health indicator?

*"Picture a pasture open to all. It is to be expected that each herdsman will try to keep as many cattle as possible on the commons. [...] As a rational being, each herdsman seeks to maximize his gain. [...] Adding together the component partial utilities, the rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd. And another; and another.... But this is the conclusion reached by each and every rational herdsman sharing a commons. Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit- in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all." (*Hardin, 1968)

Soil suffers from the so called "tragedy of the commons" (Hardin, 1968). The image given in the original paper corresponds surprisingly well to our current situation. Competing interests maximizing their personal utility in their usage of limited soil resource often don't converge to an optimal situation for society. Our current institutions fail to efficiently manage soil. This is due to multiple causes.

1) The so called "Tragedy of the Horizon": environmental problems become serious at time horizons that are not those of our institutions. It has been described in a famous speech by the governor of the Bank of England Marck Carney. "The catastrophic impacts of climate change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no direct incentive to fix." (Carney, 2015).
2) Underestimating non-linear changes and low probability events: Markets are not well equipped to tackle threshold where heavy non-linear changes are triggered, or low probability "tail events" (Barberis, 2013). This is partly due to psychological bias but also to the mathematical development of finance that attempts at rationalizing the course of society with probabilistic laws with underestimated "tails". While the current state of our soils may be very sensitive to extreme droughts that occur only once every century, market doesn't put incentive on mitigating the effects such an event could have because this risk is not included.
3) Externalities when a portion of the cost associated with a good's production is borne by an entity that doesn't have any influence over the related production decisions. In the case of soil, an example is the cost of water sanitization that is not borne by the land-user who is however partly responsible for part of the associated cost (Brown, 2018).

While the tragedy of the common only leads, in some cases, to some inefficiencies with manageable impact, it can also lock us in a trajectory toward a state of our earth system unsuitable for the existence of human societies. This trajectory must be avoided, and the causes described above must be addressed.

A possible approach is to try to evaluate the soil capital and the associated "ecosystem services". For multiple reasons this is however a difficult task to perform and the efficiency of the approach can be doubted (Baveye et al., 2016). One of the reasons is because it doesn't help solving "tragedy of the horizon" and that such a valuation often neglects the non-linearities. Sudden loss of one hectare of soil could be simply associated with the loss of the value of all the products that could have been grown on it. However, one would be very short-sighted in considering that loss of 90% of European soils would result only in a loss in value equivalent to the products that could be grown on this soil.

We need a different approach at the crossing between top-down regulation, accountability of actors, compromises between stakeholders and positive incentives. What the nature of the policy should be is not our purpose to debate here. However, such a policy will need:

1) A science-based indicator of performance to make sure that the implemented policy go in the right direction and are ambitious enough to avoid putting the society on a dangerous trajectory.
2) Strong narratives to communicate to the general public for this policy to be supported.

Science's role is not making policies but to make sure that the public debate is aware of the long term or "rare" consequences of these policies. Science can propose different scenarios to inform the public decision. This is the role we see for a soil health index: extend, through science, the horizon of decision making to account for long term effects, externalities and extreme events (see figure 1).

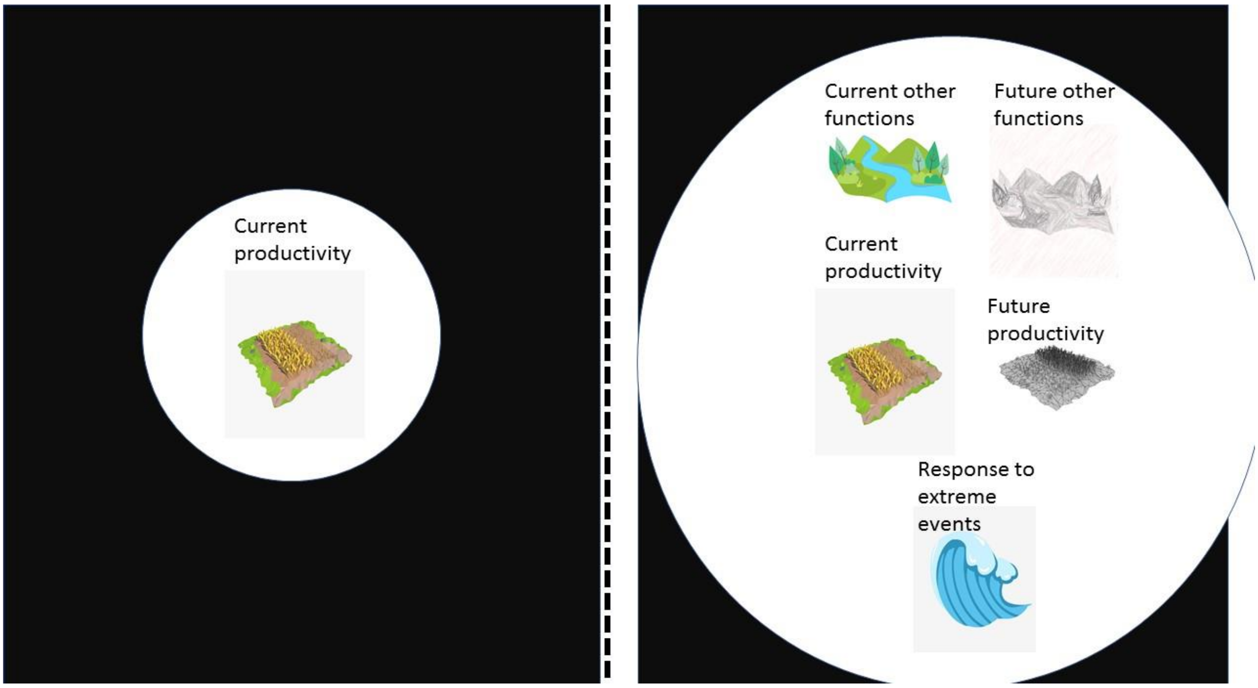

Figure 1: Role of our soil health index: extending the horizon of decision making to account for long term effects, externalities and extreme events

2. Who is our public?

The question of soil health concerns a multitude of different stakeholders, and therefore there is a multitude of angles from which the question can be approached. Before constructing an indicator of soil health, it is essential to determine from which angle we consider it. On the smallest scale (e.g. a farm) the soil functions are usually maximized in order to lead to a short-term efficient biomass production. The objectives directly concern the land managers and provide a return on investment. When the angle of approach widens (e.g. a country), the same functional soils are associated with long-term sustainability objectives such as, for example, mitigation of climate change or maintenance of biodiversity. In this case, the return on investment materializes at a societal level. Schulte et al., 2019 particularly underlines these two different approaches by distinguishing the functional objectives from the societal objectives (see figure 2).

As part of our soil health indicator, a societal approach is considered. As such, on a small-scale approach, a stakeholder taken individually may not directly feel concerned by soil health and may even consider it as suboptimal for his own land use. This is an aspect of the tragedy of the commons discussed above. While some aspect of soil health may lead to win-win improvement for farmers and water treatment facilities, they may, for example, not be a win-win improvement for farmers and fertilizer producing companies. Rather than trying to find co-benefits at all cost we think it is important to acknowledge potential trade-offs. Policy making is made of compromises and it is its role to compensate for what a certain stakeholder may lose whereas the society experiences overall gains.

Moreover, it is important to distinguish between soil issues that affect long term sustainability or efficiency of processes outside of the scope of the land user from ones that affect short term efficiency of biomass production. The second issue doesn’t require the soil health concept to be elaborated since the short-term interest of the farmers are already aligned with the necessity of solving it. However, issues that fall in the first category are to us where the Soil Health concept is of most importance to reconcile whole society's interest with the one of the land managers.

Considering soil health as a societal problem does not mean that such a definition cannot be used or reported on an individual scale. This soil health indicator can be of use by individual stakeholders, enabling to see further than the perspective induced by a short-term thinking market-logic and provide a long-term perspective. Does my city risk flooding in case of heavy rain? Will my children still be able to cultivate the same soil, or will it already have eroded away? Those are questions that fall off the short-term thinking and that do concern our farmers. For example, Anne Schelhaas dairy farmer on peat soil mentioned this kind of concern during the interviews led within the challenge.

Our approach is to take a societal angle. We think any citizen should be concerned about “Soil Health”. Therefore, the concept of soil health we develop, while still meaningful for individual land-users, takes all its significance in case of multi-stakeholders’ discussions.

Soil Function	Functional objective (farm scale)	Societal objective (EU/national scale)
Primary production	Provide farm income	Self-sufficiency
Water regulation & purification	Minimize water stress and provision of clean drinking water	Sufficient quantity of good quality
Carbon sequestration	Soil structure and functioning	Mitigation of climate change
Biodiversity	Supporting functional biodiversity	Supporting both functional and intrinsic biodiversity
Nutrient cycling	Valorization of organic nutrients (Minimize expenditure on fertilizers)	Developing a circular bio-economy

Figure 2: Functional and societal objectives associated with soil functions. Retrieved from Schulte et al., 2019

3. A discussion on scale

When discussing soil health, a discussion on scales is inevitable. Having a healthy soil does not mean the same thing at a plot, watershed, national or international scale. Scale is important for two reasons.

The first one is that different soil issues will have different relevant scales of study. When discussing soil sealing, a watershed scale may be relevant. If discussing soil carbon storage, a national or international scale may be more relevant. If discussing soil organic matter content, the plot scale may be enough to reach a conclusion.

The second reason is that locally achieving healthy soil should not be done by exporting the issue outside of the scale of study. If being able to have healthy soil in Europe relies on unhealthy soil in south America either for nutrient supply or for compensating the loss in productivity, we may be missing the point.

Since soil health aims at aligning soil management with UN SDGs that have a global significance, the soil health concept should not lose track of this global scale especially when it comes to nutrient supply and food security. We will come back to this discussion about scale when we will discuss in more details our proposal of a soil health index. When necessary we also highlight what is the spatial significance of the concept discussed.

4. "Sustainability concepts": a benchmark

The question of developing "sustainability concepts" is a long standing one that ranges beyond the field of soil. We here shortly review some of these indicators.

4.1. Non-related to soil

4.1.1 Climate

The first, most obvious, comparison can be done with climate. While the first scientific consensus about global warming came in the 80's it took 40 years and intense work from the IPCC before it transformed into (still insufficient) global action. The efficient tool that was developed and refined over the years is the use of **scenarios**. By estimating yearly global emission and different possible trajectory, scientists could draw **different possible futures** until all societies reached in 2015 a relative consensus of "staying well below 2°C". If this goal was not attained, clear definition of the consequences on our daily life were drawn (rising water level, droughts, increase of extreme water events etc…). Setting this **clear boundary** was much more efficient than loose urge of “lowering emissions” or “save energy”. It served as an objective that society could hold economic and political decision maker accountable for.

The idea of **trajectories** that structured the discussion about climate must also be retained when discussing soil health. What matters is not so much whether greenhouse gases emissions are too high now but whether we’re on track to reduce them in a sufficient amount every year.

4.1.2 Planetary boundaries

The concept of **“planetary boundary”** introduced by Rockström et al. in 2009 is a popular concept that extended the concept of boundary for climate to other Earth System processes such as freshwater use, land-system change, biosphere integrity etc.

While staying within these boundaries doesn’t ensure that **SDGs** are being reached, it is a prerequisite for it.

Once boundaries that shouldn’t be crossed are clearly defined, a sense of emergency is created that may lead to action.

Recent assessments of “planetary boundaries” compare “business as usual” scenarios to inform potential options for society (Bodirsky et al., 2014, Springmann et al., 2018, Conjin et al., 2018).

4.1.3 UN Sustainable Development Goals (SDGs)

The definition of soil health according to the challenge is “the capacity of a specific kind of soil to function, contributing towards achieving the UN Sustainable Development Goals (SDGs)”. We highlight here one pitfall surrounding SDGs to make sure the soil health concept we build avoids it. One of the issue of SDGs is indeed the risk of “cherry picking” that doesn’t account for the interaction between different SDGs. This bias is common in the **Environmental, Social, and Governance (ESG)** financial rating that is often not discriminating organisations that are really efficient in achieving SDG from others (Maniora 2017). An oil company may argue that it contributes to “providing cheap energy for all’ which is in line with SDGs 7, 8 and 9 and end up having a very good **ESG rating**. This however doesn’t consider the fact that not complying this SDG 13 “climate action” undermines all other SDGs. There is indeed little chance that there will be decent work and economic growth in a planet warmed at +4°C.

In other words, while we should manage our soils in order to get closer to achieve SDGs it shouldn’t provide a platform for “cherry picking” based greenwashing. As already mentioned, when discussing planetary boundaries, we need to clearly identify boundaries that are absolute values that should not be crossed and then only try to achieve SDGs within those boundaries.

4.2 Related to soil

Soil quality indicators have been reviewed recently (Bünemann et al., 2018) and we simply highlight and extend some of the conclusions that are relevant to the construction of our soil health indicator.

4.2.1 Soil threats

The approach through soil threats has often been proposed to communicate about the importance of caring about the soil. However, the identified threats are very different in nature and their spatial relevance is very heterogeneous. Attempts to combine them in a “soil degradation” score has led to a loss of interpretability that doesn’t enable a robust debate. Finally, soil threats and the resulting degradation has not always been linked with loss in certain soil functions and subsequently soil-based ecosystem services. (Bünemann et al., 2018)

Rather of a list of “threats” to the soil or general assessments like “30% of the soil is degraded” that are not always meaningful for the average person we need to be able to tell a full story that means something to the different stakeholders. How would an unhealthy soil affect them? How do we put in the same story threats so different in nature like erosion, compaction and organic matter loss?

4.2.2 Cornell Soil Health

The Cornell approach shows two main shortcomings that we wish to overcome. The first one is around the interpretation of their indicators that is mainly done by comparing them to a statistical distribution. However, being the “most healthy soil” from a given region doesn’t necessarily mean for a soil that it is “sufficiently healthy”. In other terms, this approach doesn’t inform us about the ability of soil ‘supply of ecosystem services’ from a given region to match demand.

Besides, the evaluation of soil health is static and informs about the status of soil at a given point in time while the societal relevance of soil health emerges from the projection of current management practices in the long term. What matters to society is not as much to what extent the soil is currently able to deliver its services but to what extent it will be able to do so on the long term, in the face of extreme events and when some of its “crutches” (see later) are removed.

4.2.3 The LANDMARK project

Landmark Project that was part of the previous Horizon 2020 funding provides a robust framework to evaluate demand and supply of soil functions at different scales (local, regional, EU) depending on soil properties, land use and management practices. This framework is efficiently able to deal with uncertainties.

While there is certainly an ongoing scientific discussion on this project we will later refer to “LANDMARK approach” as a way to refer to the evaluation of “soil functions” based on information of soil properties X Climate X land use and management practices at the appropriate scale.

5. A short discussion on psychology

It is an ongoing debate in psychology whether optimistic or pessimistic messages work better at inspiring behavioural change (Kidd et al., 2019). The “optimism” paradigm may however have had more media attention recently leading to a general belief that all communication about environmental issue should be framed in a positive way. The consensus seems to hint towards the fact that message that provokes “fear” will only be efficient in producing behaviour if they are accompanied with a pathway to act on the causes of that fear and prospective of improvement (O’Neill et al., 2009). Otherwise the constant appeal to fear leads to apathy and numbness. This means that to be efficiently communicated and lead to action, a soil health index does not necessarily have to be framed positively but it should be comprehensive enough for each stakeholder to know how one may be affected and what role one can play and how one can take efficient action.

We thus think that a discussion about soil health should give a sense of emergency if there is indeed a legitimate scientific reason to think that the current trajectory leads to havoc. However, not all soil degradations fall in that category and it is unnecessary to try to produce a sense of emergency if we are not able to deploy a full story describing the irreversible consequences of today's’ action.

6. Conclusion

Our benchmarking highlights certain points that we consider essential when it comes to developing an indicator of soil health. Exploring them also mean answering the core questions for sustainability science identified by Kates et al. (2001) in a highly cited Science paper.

Climate change has become a real emergency once it has been described using scenarios and trajectories in the future. The assessment of soil health must rely on a projection in the future (see point 6 figure 3). Where relevant, boundaries should be established. As pointed out by Kates et al. (2001) they serve as a warning beyond which a serious degradation of the nature-society systems can be expected (see point 4 figure 3).

As the role of our soil health indicator is to prevent unwanted long-term changes that short-term oriented management would produce, we directly tackle another point of Kates et al. (2001) paper; market should not be the system guiding the interactions between nature and society, but scientific information should (see point 5 figure 3). LANDMARK project is a source of inspiration by its inclusion of soil functions into soil health assessment. The last point (see point 8 figure 3) underlined by the paper will be explored in greater detail in part III of the report.

1. How can the dynamic interactions between nature and society – including lags and inertia – be better incorporated in emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?
2. How are long-term trends in environment and development, including and population, reshaping nature-society interactions in ways relevant to sustainability?
3. What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?
4. Can scientifically meaningful “limits” or “boundaries” be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?
5. What systems of incentive structures – including markets, rules, norms and scientific information – can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
6. How can today’s operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?
7. How can today’s relatively independent activities of research planning, observation, assessment, and decision support be better integrated into systems for adaptive management and societal learning?

Figure 3: the core questions for sustainability science identified by Kates et al. (2001)

II. Our definition of soil health

We build our definition of soil health on the last section where we analysed what where the criteria for its success and benchmarked the success and shortcomings of other sustainability associated concepts.

We identify six prerequisites for a definition of soil health that would help provide a framework for non-market-based management of soil.

1) Soil health should directly evoke a strong narrative understandable by citizen and policy maker. This narrative should clearly answer some societal questions such as "What will happen if we don't care enough about our soil? Why should I be worried? Are we on a dangerous trajectory that we should change? What can we do to protect soil then?".

   The narrative needs to provide both a sense of emergency and a way to tackle this emergency. This is at the heart of the distinction we make between "soil quality" and "soil health". Bad "health" associates with possible death and emergency for society to find a treatment and already holds a strong narrative. Low "quality" only relates to disfunction that only matters to the land user.

2) Soil health related metrics should when necessary be interpreted with process-based boundaries. Scientifically meaningful boundaries are however not always possible to define, and this constitutes a research question (see point 4 of figure…). When clear boundaries are defined, they give a clear indication that policies should enable us to stay within those boundaries as a prerequisite to achieving SDGs.
3) Related to the first point on narrative. The concept of soil health shouldn't inform us only on the current state of soil at different scales but also on the future according to different scenarios. We should be able to make the difference between a "currently unhealthy soil" on a trajectory toward "health" and a "currently healthy soil" submitted to "unhealthy" management practices.
4) Soil health is not an intrinsic property of soil: it is a feature that emerges of the interaction between soils and society. We won't be informed about "soil health" only looking at soil, we need to look at the society that lives around it.
5) Because of this last point and because what we define as "a society" will have different meaning at different scale (a village, a region, a nation, the EU). The exact way of using the soil health definition will vary slightly depending on the scale. However, the guidelines we provide should be applicable at all scales.
6) Soil health information should account for the shortcoming of market-based management namely: "tragedy of the horizon", underestimation of non-linear changes and low probability events and externalities.

1. What narrative for soil health? What do we aim for?

As mentioned in prerequisite 1), we need a narrative to explain why we would like to make our soils "healthier". Providing this narrative is also a way to describe what soil health is. This narrative can be developed in three different dimensions.

a) Resilience and robustness

The first direction is what we further define as soil “resilience and robustness”. Resilience can in fact be understood in two different ways. The first one, engineering resilience, measures the rate of recovery of the system after a disturbance. The second one, ecological resilience, is the amount of disturbance the system can sustain before flipping to a completely different state. “Engineering resilience” is often discussed together with the concept of “resistance”, the ability of a system to withstand a disturbance. In the rest of the discussion, because they both relate to the response to a “disturbance” we put the “resistance” and the “engineering resilience” concepts together and refer to them with the general term “robustness” while we will refer to “ecological resilience” as “resilience”.

Concerning “resilience”, because of positive feedbacks, systems can in some cases be pushed in a completely different state of functioning with large societal consequences. While different stressors will slowly push the system next to the tipping point, crossing it is often triggered by an extreme event. One famous example of tipping point that was crossed during an extreme event is the “dust bowl” of the 1930s. It was the consequences of a combination of poor management practices (stressor) and an extreme and long-lasting drought (extreme event). While the possibility of such “dust bowl” events to happen again is uncertain it shows the necessity to foresee those kinds of large-scale transitions that may be triggered by extreme events. it is a necessary effort of the scientific imagination to consider all possible implications of extreme events and identify weak points. If American pedologists and climatologists from the 1920s had foreseen what was coming they may have avoided one of the biggest ecological disaster of the 20th century. This is precisely what we think some of the research on “soil health” should be dedicated: provide this “cross-disciplinary” insight in the future and deliver the warnings that scientist from the 1920s could have provided (Seager, n.d.).

We highlighted here an example were the crossing of a tipping point is triggered by an extreme event, this is however not always the case and crossing the tipping point can also happen when the amount of stress crosses a certain “threshold”. In that sense, discussing tipping points leads naturally to defining **threshold** or **boundaries**.

Beside the crossing of a “tipping point” extreme events can push away systems from their original state for some time until they recover. Even if no “tipping point” is crossed, this temporary shift can have heavy consequences on yield for example. A “healthy soil” is one that enables that in case of extreme event we don’t risk a loss of productivity that would affect food security. Soil plays a role in this “robustness” to extreme events through the buffering of water availability, the proper drainage after heavy rainfall events and the ability to still provide good condition for plant growth in case of extreme events. Looking at the soil from that angle answers the following questions: what will be the consequences if we have a long-lasting drought or a heavy rain? How can we manage our soil to better bear with the consequences?

b) Independence from crutches

Part of our current productivity is reliant on heavy external inputs (irrigation, nutrients, pesticides, fossil fuel to power machinery, protein crops for meat and dairy production). These external inputs pose two kinds of problems. The first being that their availability may be limited in the future. Either because of shortage of resources (mineral phosphorus, irrigation water, fossil fuels) or because of disruption in the supply chain due to instabilities (pandemics, geopolitical crisis) (Rhodes, 2017). The second being the potential side effects of those external inputs: eutrophication in case of excessive nutrients, impacts on biodiversity for pesticides, global warming for fossil fuels, competition with other water usage or salinization for irrigation, cost for farmers (nutrients, irrigation and fossil fuels), export of externalities for protein crops.

While these “crutches” that our agriculture relies on will certainly remain necessary in a lot of contexts a general goal is to reduce our dependence on them to a reasonable amount. This is the second dimension of the narrative.

c) Multifunctionality

The last dimension of the narrative relates rebalancing the current usage of soils. It has so far mainly been optimized for biomass production at the expense of other possible functions. This multifunctionality was already part of the narrative associated with the horizon 2020 as shows the emphasis that the LANDMARK project puts on it.

The functions considered by the LANDMARK project are “water purification and regulation”, “biodiversity and habitat provision”, “climate regulation”, “nutrient cycling” and “primary productivity”. Some aspects of “nutrient cycling”, “water purification and regulation” and “primary productivity” also relates to “independence from crutches”. This redundancy is however not problematic since the two narratives still develop two independent dimensions (having a multifunctional soil is different from having a soil independent from crutches).

2. What metrics do we associate with these goals and what are their meaning?

We highlight here some possible metrics that fit within these narratives, especially those that associate with process-based boundaries which fits in point 2) of the identified prerequisites or those that have recently been used in published literature. These are however simply meant to exemplify what measuring soil health could be. Discussing fully to what extent these proposed metrics are robust and if the dataset available are enough to evaluate them is beyond the scope of this report. We provide a few thoughts on these in section 4).

We also highlight the possibility of discussing those narrative beside quantitative metrics developing scientifically robust qualitative stories. As we will also discuss later, some use-case of soil health we imagine don’t require as much a quantitative evaluation than the ability to describe qualitatively different possible consequences of “unhealthy soil”.

Related to point 5) of our prerequisites we also describe which scale is relevant for the metric discussed.

- **Resilience**

Tipping point of the soil system are hard to define. The attempt by Rockström et al. 2009 was to fix a global limit at 15% of land surface being cultivated. As pointed out by Bass 2009, this limit is arbitrary and does not consider the exact management practices in these cultivated areas. He rather suggests threshold based on soil degradation or soil loss. This debate exemplifies the need for more research to define science-based boundaries related to soil both at the global and at intermediates scales. Although this discussion dates to a decade ago, we are to this day not aware of new results in this field. Beyond the ability to find a metric that we can associate with a boundary, science can also provide a qualitative exploration of a science based “story” of what could happen. This is exactly the approach of Benton et al., 2017 when they explore the possible impacts of an “East Anglian dustbowl" in a both qualitative and quantitative manner in their report about "Environmental tipping points and food system dynamics".

To evaluate engineering resilience, virtual "stress test" on the soil through process-based modelling to measure their exposure to a crisis could be performed. This is similar to what is done in financial institutions to measure the exposure of their portfolio to a potential crisis. This approach has recently been used to study the response of six different soils to climate change (Bonfante et al., 2019, 2020). The variable considered was biomass production, but the approach could be extended to other functions.

- **Independence from crutches**

The fertilizer crutches:

Related metrics and interpretation are already included in the LANDMARK project under the term "provision and cycling of nutrients". The more efficient the soil is at nutrient cycling the more independent the agricultural system is from organic and mineral fertilizer. This has mainly a plot significance.

At the scales above can be asked the question of nutrient balance. Achieving a zero-net imbalance can be considered a general goal to achieve "soil health" at each of these scales, especially at the EU scale to avoid the building up of "soil health" in the EU at the cost of unhealthy soil in other countries. We propose the nutrient balance (difference between in and out) to be a metric related to this reliance on crutches. It is meaningful at each scale (apart from plot scale) and an absolute goal of zero imbalance can be considered criteria for a healthy soil.

The irrigation crutches:

Related metrics and interpretation are already included in the LANDMARK project under in the water storage part of the "water purification and regulation" function of soil. This is of plot relevance.

Fossil fuel:

Working the soil requires some energy. Direct energy consumption of agriculture is estimated to be 2.8% of final energy consumption in the EU (non-taking into account the production of fertilizers and pesticides) (Eurostat, 2019). This is mainly due to the use of machinery, heating of livestock stables and greenhouses. The necessity of using machinery and especially powerful ones is directly related to soil management and tillage. Like any other sectors, agriculture will have to go through an energy transition (either forced by scarcity of fossil fuels or by climate change policies). This transition is based on three pillars: reduction in energy consumption, increasing efficiency and changing energy source. Because the first pillar is an essential one, we propose the metric associated with reliance on fossil fuels to rather be one of "reliance on energy consumption" in J/ha. This is meaningful for decisions at all scales and can be evaluated differently at each one of these scales (farmer self-reporting of his energy consumption, national and subnational statistics from Eurostat etc.…)

Pesticides:

Reliance on pesticides can vary depending on soil suppressiveness (Mendes et al., 2011). We are however not aware of any metrics related to suppressiveness. Given the variety of products used in different context it is difficult at this stage to define a metric that accurately describe reliance on pesticides.

We highlight here a potential trade-off between reliance on pesticides and other dimensions of soil health. Indeed, while certain aspects of soil health could be increased by no-till practices, these practices often rely on the use of herbicides.

- **Multifunctionality beyond biomass production**

All the metrics related to multifunctionality have already been explored in the LANDMARK project. Following Maron et al., 2017 and Manning et al., 2018 the ideal procedure to build a "supply-benefit relationship" around those functions is a threshold one based on demand of those same services. Demand can be mapped at different scale by looking at the policies relevant for this scale that should reflect (even imperfectly) the democratic societal demand of those services. Importantly, "water purification and regulation" is mostly significant at the watershed scale, "biodiversity and habitat provision" at the regional scale and "climate regulation" at the national or European scale.

We highlight how the discussion on scale and "independence from crutches" interact with this narrative and the associated metrics. Multifunctionality has indeed been assessed at different scale in the LANDMARK project but one of the conclusions was that "a mathematical matching of supply and demand is neither possible nor realistic given the high intra- and extra-European trade in agricultural products and resources.". This last point relates to the one about crutches and scale discussed above. If matching demand for services is done at the cost of importing some from outside the EU, there is a chance that the "healthy soil" that we could achieve in the EU relies on "unhealthy" ones elsewhere. A net-zero imbalance in nutrients is a first step to avoid this.

Besides, as stated by Maron et al., 2017, it is not so much the current supply of ecosystem service that matters as the future trend and its potential extinction (Fig. 4). This depends on current situation and future trend that depend on management. We discuss it in the next section.

Category	Definition	Threshold
Functionally extinct	Service no longer supplied in the region and is practically unrecoverable	Lost
Dormant	Service no longer supplied in the region but is potentially recoverable	
Critically endangered	Current levels of demand exceed supply and the ratio of supply to demand declining or expected to decline	Undersupplied
Endangered	Current levels of demand exceed supply; ratio of supply to demand is stable but supply is declining	
Stable but undersupplied	Current levels of demand exceed supply; neither supply nor ratio of supply to demand declining	
Vulnerable	Ratio of supply to demand is declining or expected to decline such that supply is likely to be insufficient to meet demand within a set time horizon	At risk
Least concern	Supply currently meets or exceeds demand, and does not meet the criteria for Vulnerable	Secure
Data deficient	Inadequate information is available about either or both of supply and demand to assess the level of threat	n/a

Trends in Ecology & Evolution

Figure 4 : The proposed threat categorization framework for ecosystem service (copied from Maron et al. (2017)).

3. Predicting future trends under different scenarios

As mentioned in point 3) of the prerequisites, to fully inform decisions and create a sense of emergency, we need to go further than simply informing on current state of soil health. A soil may be currently very healthy according to all narratives but subject to heavy erosion rate for example. Then there is a good chance that its health will diminish over time ultimately completely vanishing if erosion goes on. A good assessment of soil health must account for the projection of the current state of soil in time under different management scenarios.

What we propose is similar to recent assessment of “planetary boundaries” that compared a “business as usual” scenario to inform potential options for society (Bodirsky et al., 2014, Springmann et al., 2018, Conjin et al., 2018). While these studies had a global scale significance because of the concept of planetary boundaries itself the same projection and scenarios could be imagined at different scales.

Scenario analysis has been added to the core questions of sustainability science of Kates et al. (2001) by Swart et al. (2004) and defined as follow: “coherent and plausible stories, told in words and numbers, about the possible co-evolutionary pathways of combined human and environmental systems. They generally include a definition of problem boundaries, a characterization of current condition sand processes driving change, an identification of critical uncertainties and assumptions on how they are resolved, and images of the future. The characterization of the nature of human and environmental response under contrasting future conditions is key in scenario formulation. Reflecting respect for the uncertainty inherent in such systems, scenarios are neither predictions nor forecasts”

We are only aware of only one study that applied this kind of scenario analysis approach for sustainable multifunctional land uses at a watershed scale (Brown, I., & Castellazzi, M., 2014). The SoilCare project[1] is also working on scenarios at the European scale.

Depending on the scale, the available data and the available expertise and the public, the discussion of scenarios can range from fully qualitative to fully quantitative. Proposing scenarios is also an essential part of acting as an “honest broker of science”. (Pielke, 2007)

4. What do we measure to assess soil health?

As mentioned in prerequisite 4): “soil health” doesn’t just depend on soil: it is a function of soil properties, climate, land use, management practices and even of the societal demand for some ecosystem services. Soil health is not an intrinsic value of the soil but more a description of the relationship we have with it. Soil health is thus not measurable simply by accumulating proxy indicators of soil only. Ideally, we would be able to go to every single farm, gather all the possible data about its context and discuss the health of its soil within its particular situation. This would be the best way of both avoiding top-down regulations that are simply unable to grasp the singularities of every situation and having the most complete dataset to avoid uncertainties in the assessment of “soil health”.

This is not an option completely out of reach. Some national monitoring scheme in Europe are already very precise and new technologies progressively enable the collection and management of increasing amount of data. Dealing with incomplete dataset is however a common procedure in many fields like weather forecast modelling. Missing data can be extrapolated, possibly at the cost of increased uncertainty or some part of the goals we mentioned can be neglected. Because some aspect of soil health relies on discussing different possible qualitative stories, uncertainty is an inherent part of the process. This overall depends on the specific usage of the “soil health” concept and we will discuss it in the next section. In some use cases, we argue that “soil health” doesn’t have to be something that is being measured but rather a methodological framework for multi-stakeholder discussion about land use.

We think discussing here a precise set of “indicators” that should be measured is out of reach and would require more research. The LANDMARK project has thoroughly explored methodologies to choose such indicators and some of them already go beyond soil. The necessity to be able to draw trends rather than simply informing on current state that we discussed above may necessitate some additional data than has previously been discussed in literature. Our emphasis on new narratives like the reliance on crutches will require additional data.

5. What “soil health” for what scale?

[1] https://www.soilcare-project.eu/en/

The narrative we propose as an answer to prerequisite 1) are applicable at all scales. However, like it is the case in the LANDMARK project, the specific metrics associated with those narratives will vary depending on the scale and with data availability. In that sense, we believe the above definition meets prerequisite 5). Further discussion on scale is provided in the part about "How the definition can be used".

6. How does this definition covers the shortcoming of market-based management

As mentioned in prerequisite 6) the concept of soil health should provide information that enables to overcome the "tragedy of the horizon", the underestimation of non-linear changes and low probability events and externalities.

Underestimation of non-linear changes

Ecological resilience and the possibility to suddenly shift to an alternate state of functioning is one kind of non-linear change that market fail to fully foresee. Through the "resilience" narrative, the concept of soil health we propose warns about such nonlinear changes.

Underestimation of low-probability events

Extreme events are low-probability events that we integrate in our definition of soil health through the "resilience narrative" and more specifically the focus on "robustness".

Externalities

We cover the "externalities" through the "multifunctionality" and the "independence from crutches" narratives.

Tragedy of the horizon

We cover the "tragedy of the horizon" to some extent in the "independence from crutches" narrative where we discuss future resource scarcity. The prediction of future trends under different scenarios also warns about long term effect of current practices.

7. Conclusion: what does it mean for horizon 2027 research?

From the discussion above we highlight different research gaps that naturally stem from the approach we describe

a) Soils have still been very little investigated through the angle of "tipping points" and "alternative stable states" or in other terms in the "ecological resilience" language. When asked about it, prof Tim Benton confirmed that "There is certainly not a good research base to understand how soil properties, microclimate, microbiome and yields might interact and whether there may be tipping points in functionality...But I wish one existed!". Personal communication with Prof. Richard Bardgett highlighted the same direction of research as a future hot topic (Bardgett, R. D., & Caruso, T. (2020)). Once research will be able to describe the risk of some dustbowl-like events we will be closer to define clear boundaries that should absolutely not be crossed.
b) What we called "robustness" that is the ability of the system to withstand perturbations and recover has been more investigated (De Vries et al., 2012, Mandakovic et al., 2018). However, based on our own review, we think the current literature doesn't always connect the studied "robustness" to its societal meaning. Among all disturbances, we propose here

to focus on extreme weather events. The ultimate goal will be the ability to develop a (quantitative and/or qualitative) modelling framework to run the "stress test" mentioned above. We are arguably not so far from there given that similar "stress test" were performed by Bonfante et al., 2019 for example focusing on primary productivity.

c) In the "independence from crutches" narrative, the question of the "reliance on fossil fuels" has to our knowledge been little explored (Heichel 1976, Pfeifel 2006). Future resource scarcity (phosphorous, fossil fuels) and their impact on soils and agricultural production would also critically need further research. This relates to the next point as well.

d) We see a large potential in the development of soil and land use scenarios that describe quantitatively and qualitatively different possible futures taking into account all relevant variables and their co-evolutions: resources availability, change in diet, climate change. As mentioned above, such scenarios already exist for the food system (Bodirsky et al., 2014, Springmann et al., 2018, Conjin et al., 2018) but their description of soil is limited. Beyond these global scale assessments, delivering a framework (for modelling but also for expert based assessment) within which decision maker at the watershed level could imagine different scenarios can be a deliverable of future European research projects.

III. How can this definition be used?

It’s not because the definition of soil health we propose provides new information that market will solve the issue. Climate science is able to deliver robust scenarios and fully inform markets about the long-term consequences of today’s choices but we are still not on a reassuring greenhouse gas emission trajectory. The way the soil health concept can be used and how it can be communicated is thus critical if we are to achieve “healthy soils”. As mentioned before, how the soil health concept can be used depends on the scale.

1. The farm scale

As mentioned by Schulte et al., 2019 functional objective may differ from societal objective (Fig 2). However, long term effects, resilience to extreme events and independence from crutches may matter to land users as well. Insights on these could be provided by consultants or independent testing services to inform current management practices and give positive incentive for a healthier soil.

2. The watershed scale

The watershed scale is the scale where our definition of soil health could be most meaningful. In Belgium, an public service called GISER [2]can be contacted whenever an erosion issue is detected in a municipality. They come for free with a scientifically sound expertise and organise the discussion between stakeholders to find a solution. The experience is detailed detailed here [3](in French) and we think it could easily generalize to soil health. The need for such independent advice has been highlighted by Rene Bos from Ijsselham during the live event ‘Soil at Dutch farms’ of the challenge.

Concretely, the public service would be called to provide a qualitative and quantitative assessment of “soil health” in the watershed. It would also provide a comprehensive story of different options describing scenarios. These scenarios could be developed with help from a general modelling framework that would be the deliverable of a horizon 2027 research project. The public service would then organize the discussion with all stakeholders to converge toward an optimal management of the watershed. Aware of the soil health expectations in other watershed or at other scales (regional, national, European) it would also serve as an intermediary to stand for the interests of this different other scales or locations.

3. The national and European scale

Because achieving goals may require some profound changes, such organisms will need a legitimacy from one of these two bigger scale to make sure that the outcome of the discussion doesn’t fall short of ambitions. Besides, only these scales can provide compensatory mechanisms to land users who may have lost in terms of functional objective to achieve societal objective. This shortcoming has been identified by GISER, if the advice provided by this independent public service are not accompanied by legislation there may be a lack of incentive to achieve sufficient ambition.

[2] https://www.giser.be/gestion-integree-sol-erosion-ruissellement/expertise-de-sites-inondes/
[3] https://www.youtube.com/watch?v=T3eG-PM5-8A&feature=youtu.be

Additionally, some expectation (independence from crutches, climate regulation function) would not necessarily be considered important at a watershed scale and can only stem from national or European considerations.

Discussing soil health at those scales will be necessary as well. When building global Policies like the CAP, policy maker will be able to evaluate those policies qualitatively and quantitatively in the light of soil health trajectories according to different scenarios. This approach is to some extent already undertaken by the SoilCare project[4] but we think what we propose goes further. Concerning hard boundaries whose crossing leads to irreversible change like erosion: those policies need to be sufficiently ambitious and avoid loosely defined objective whose ambitions can easily be lowered. If the public is sufficiently aware of such soil issues it will be able to seize itself of the subject and push for ambitious policies through vote or other actions similarly to what happened in the last years for climate.

4. Conclusion

The ideal set-up for a thoughtful discussion about soil health is one where the stakeholders and a scientist sit around the table and he acts as an honest broker of science providing quantitative insights on different possible scenarios. Soil health as we define here is a complex concept that can be manipulated quantitatively. But when the proper data to provide full quantitative information is not present, a qualitative discussion may already yield some first results.

The most relevant scale for "soil health" discussion is the local watershed one and we highlight the need for a public service to provide independent scientifically sound insights in the future and acting as a "honest broker of science". Soil decisions are complex and case specific and while what's at stake in every decision should be made understandable for each stakeholder, the methodology to provide the insights will require some specific expertise.

We think the kind of set-up we imagine as the natural use-case of the soil health concept where an independent expert sits around the table with the other stakeholders can do a better job than increasingly complex decision support systems. Indeed, as mentioned by some farmers during the live event 'Soil at Dutch farms', these are often black box that already require some learning to be efficiently used. What's more, the context specificity is impossible to integrate in such support systems. Finally, reaching a consensus between different stakeholders requires a discussion and this human interaction is essential to build trust and avoid frustration.

[4] https://www.soilcare-project.eu/en/

IV. How do we communicate about the soil?

Rather recently the idea that we had "100 years of soil left" made its way in the public media but had however no proper scientific ground (Cosier, 2019; Wong, 2019). Such estimates may be impossible to obtain accurately but this highlights the power of this kind of narrative to obtain public attention.

By emphasizing the necessity to provide the public, especially the European one with strong narratives we partly provide a path toward better communication of soil issues. These narratives provide answers to the questions: Why should I worry about current soil health and its future trends while I have lived all my life with a certain abundance of food, fuel and fibre? Is it really an emergency to worry about it? What can I do? We chose angles that we thought were meaningful: is there a risk in the long term? Is there a risk in case of extreme events? Is there a risk if crutches are suddenly removed? What services am I getting that I may not get in the future?

But in order to fully understand the answer to these questions and for the democratic debate to be fruitful, all stakeholders should have a basic understanding of the mechanisms of soil functioning. They should also be aware of the latest updates of sound science. The discussion about soil health shouldn't be just an expert debate. This is also necessary because understanding the consequences of an action is necessary to motivate it.

But the general public lacks knowledge about the functioning of soil. There is a general idea that soil is being threatened but when asked for more details, people around us generally couldn't provide further explanations, they loosely evoked "pesticides" or "nutrients" but couldn't explain exactly what was at stake. There is then currently little chance that they will support ambitious policies about soil. As stated in Baveye et al., 2016 "Regardless of the approach that decision makers end up adopting to deal with the allocation of soil resources among competing demands, it seems clear that an important component of their action will have to be devoted to educating members of the public about the huge significance of soils in their lives. Only an educated citizenry, keenly aware of the complex array of functions, and services that soils fulfil, will be able to make appropriate decisions collaboratively, or to support them through democratic channels. We are arguably very far from that now." This applies to citizen in general but also executive boards and employees of companies related to land use, municipalities' councils and policy makers.

Besides, with urban development and then globalization, humans have gradually detached themselves emotionally from the soil that surrounds them. Humans live without any concern for the soil from which their food comes from. When it comes to caring for someone or something, an emotional motivation for care is an essential dimension. As demonstrated by Kals et al., 1999 "Nature-protective behaviour cannot be sufficiently explained using a pure rational/cognitive approach." We believe that communication to society must be based on this notion as well as on more rational incentives.

In this bestseller "Sapiens" (Harari, 2014), the author Yuval Noah Harari points out that history is ultimately a complex network of stories that humans tell each other. The essence of the society as we know it is based on storytelling. They allow us to believe in most concepts that constitute the structure of human society such as nations, justice, money, etc. If hearing stories affect us it is because it triggers a reaction in the area of the brain responsible for empathy and compassion (Zak, 2014). Knowing that can help us employ this valuable skill in triggering in people the will to act to protect the soils.

1. The example of the climate collage

1.1 The idea

The same shortcomings in communication that we identified above in the case of soil is a challenge that other scientific communities face. IPCC communication to the general public has always been difficult (Corner et al., 2018). Confronted with this observation, some environmental organisations in France sponsored by the co-chair of IPCC Valérie Masson-Delmotte created a serious game called "The Climate Collage" with the goal of educating 1 Million people to the IPCC reports. The strategy is to progressively expand the number of facilitators that can make other people play. Once someone has played the game multiple times, he is able to transmit it to other people. In two years, more than 50 000 people played the game thanks to a network of 2000+ facilitators. In September 2020, 100 000 students from higher-education institutions across France will play the game.

1.2 The principles of the game

Participants are playing as a team and they need to find the cause and effect relationship between 42 cards. They build a collage explaining the story of climate change.
The session is divided in three phases. The first one that takes about 1 hour and a half and consists in placing the cards at the right place in the collage and connecting them with arrows.
Once they have a picture of the whole system, they are invited to interact creatively with it. Make drawings, add words and concepts around the cards etc. Finally, an hour is dedicated to reflection about solutions. The game requires very little material to be played: simply the 42 cards, a large paper and some colourful pens.

2. The efficiency of serious board games

2.1 Board games

Board games are an efficient way of getting a grasp on the functioning of complex systems. They don't require extensive technology and are easily adaptable. Besides, because board games are often played in groups, they allow learning not only by doing but also by "articulating knowledge" since the participants have to explain to the rest of the group the choices they make. (Wouters et al., 2013). It also allows seeing the game from the perspective of different players (Castronova et al., 2015) which is an interesting feature given the necessity of multi-stakeholder discussion about soil issues.

2.2 Serious Games

In a Meta-Analysis of 39 studies, Castronova et al. showed that serious games were significantly more effective in terms of learning and retention than conventional methods. Additionally, playing the game in group and supplementing it with discussion between the participants improves learning effects.

3. What about soil?

3.1 The specific case of soil

Corner et al., 2018 provide several principles for scientific communication. One of them is to “connect to what matters to your audience”. Compared to the climate, soil has an advantage: it is a very concrete object from the real world that most people can connect to. Soil is directly linked to food or clothes that people can easily relate to.

Another principle of scientific communication is to “tell a human story” We highlighted before the necessity to develop scenarios and expand the story about soil even in the future to answer the questions “what will happen if we don’t take care of our soils?”. We discussed the fact that soil health was not only about quantitative indicators but also about qualitative narratives. How independent are we from crutches? What will happen if we have an extreme drought in Europe? While the scientific basis should be robust and quantitative, the communication doesn’t have to be. The report by Corner et al. 2018, also highlights the need for “effective visual communication”. This is especially the case for soil that is an “unseen black box”.

We contacted a student from the Gerrit Rietveld Academie, an international university of applied sciences for Fine Arts and Design in Amsterdam (NL), who agreed to collaborate with us for the production of the visual content of the game. We wish the Rietveld student to bring in her non-scientific perspective to this product, ensuring that the content would be accessible to the more general audience it is ultimately targeting.

Furthermore, as Isabelle Stengers points out "One of the great challenges of our time is that knowledge is transformative, that it awakens the imagination, that it makes the world even more interesting, that it detoxifies from the sadness of" we know "and" it's only”” (Stengers, 2019). With this in mind, we set a game, which has for aim to awake curiosity of the public for soil and soil health. From our point of view, this would encourage the reconnection of human's affection with the soil. In addition, this system would allow different stakeholders to meet which will further encourage cooperation and practice agreements when it comes to deal with soil health.

3.2 Example of game related to soil

Board games have previously been used (RESORTES) (Speelman et al., 2014) and are currently under development[5] for participative design of more sustainable agricultural landscapes. In the case of RESORTES experiments ran with a community in Mexico showed that the game sessions created an open and active discussion among participants.

A serious game about agroecology that includes an extensive soil module is currently being developed for bachelor and high school students (Godinot, 2018)

While we suggest developing a serious game could be an original outcome of a research project funded within horizon 2027 we wished to provide a deliverable together with this report where we would create our own approach. The aim is both to provide an example of what could be such a game and lay the first basis of the work we propose.

[5] http://caes.mak.ac.ug/wp-content/uploads/2019/07/SESAM_INREF-full-proposal.pdf

4. Our game

Our approach is different from the existing games: we do not wish to directly design agricultural landscape through playing like done by Speelman et al. Our purpose is to make an accessible game that serves as an icebreaker for different stakeholders to pursue further discussion and as an information support to clearly identify the cause-effect relationships in the soil system and how collective choices can influence it.

Our game will take the form of a "workshop" lasting approximately 3 hours and which is divided into three parts. During the first part, the players become familiar with the functioning of the ground. They are gradually guided by a facilitator who reveals the different functions of the soil through a story. In the first part, the players try to reconstruct the functioning of soil in a natural ecosystem starting from the plant and slowly extending to include all biological, physical and chemical components of the soil system. Then in a second part, human influence on soils principally through agriculture is introduced and the player discovers how these changes the functioning of the system he build in the first part. The last part is dedicated to a guided discussion where the society X soil system is discussed along the three "soil health" narratives.

In the first part the players face the following concepts: mineralization, immobilization, photosynthesis, nitrogen fixation, denitrification. In the second part, the impacts of agriculture on the functioning of the soil and its interactions with other spheres are exposed. The players familiarize themselves with the following terms: Deforestation, pesticides, tillage, manure, fertilizers, irrigation and use of machinery. In the last part, the consequences of agriculture are discussed. The players put together everything they have learned so far and come to understand the consequences of certain practices on the ground as well as the issues that threaten it. The following threats are addressed: soil erosion, air, water and soil pollution, water runoff, flooding, CO_2 emissions, soil salinization, nitrogen emission, nutrients leaching. Like in the Climate Collage, these three parts are followed by a creative session and an open discussion about potential “solutions”. Depending on the public these solutions can be related to daily life for regular citizen, to the specific activity of the company if the game is used for a company team “team-building” session or have to do with different policy or management option if the public is composed of land users and policy makers. The main input comes from the players, but the trainer is there to re-explain concepts that were not clear.

Each session is led by a facilitator, who guides the players and provides them with scientific explanations. Once a player has completed his first session, he can himself become a facilitator if he participates to a training.

The first printed version will be in English but can easily be translated. The original game is intended for an audience who has no background in soil science or science but who has a certain education, but this can easily be adapted to different publics like it is the case for the climate collage.
For example, an "expert" version can be imagined, intended for a more advanced audience. An easier version can also be developed if needed, for younger audience such as kids.

4.1 The visuals

Using the right visuals is a crucial step for the players to be able to form a mental image of the soil that he will remember. Different approaches are possible from the fully "informative" one to the more "sensitive" one. Our collaboration with Rietveld Academy led to a version of the visuals appealing to the sensitive dimension of understanding. One side of the card is occupied by a very sober illustration evoking abstractly the concept and the other contains all the explanations. When put next to each other, the cards form together a poetic picture of soil functioning. Interestingly, the student we collaborated with had no previous experience of the soil before collaborating with us and they learned about it by playing the game. This results in original representations of the soil system that go beyond the usual graphics.

These illustrations correspond more to a "general public" use-case. For more "corporate" usage, some more "self-explanatory" illustrations could be imagined. As described before, the current stage of construction of the game is meant as a thought experiment to inspire further developments. A schematic description of one session and the current stage of graphic development can be found in Annex 1.

5. Use Cases

A first sector in which it will be interesting to apply the game is the educational one. It is essential that future generations can understand the issues related to soil health since they will be the one enduring the long-term effects of potentially unhealthy soils. No matter what professional direction various high school students may take, basic knowledge of the ground can be important in different professional spheres. Our game is for the last two years of high school. In this sector, the game can be led by a trainer but also by teachers who feel comfortable with the subject.

In the public sector, playing can be a major ally when it comes to bringing different stakeholders around the table. Municipalities and public bodies can request a workshop to receive advice and possible support on the various problems that may exist related to the soil (conflicts between stakeholders, lack of awareness among citizens, need to make a decision regarding a specific soil related issue). For example, a municipality can offer this type of workshop for its decision-makers, farmers and members of the municipal council. First, the cooperation required to participate in the game encourages the different players to communicate and express their own points of view. Second, introducing scientific explanations can help make more objective decisions at the local level. Third, it can provide decision-makers with tools to understand the reality of farmers and their concerns. The public service we mentioned earlier as the "honest broker" of science at the watershed scale could be easily trained to be a facilitator and introduce his session with the game as an icebreaker.

Lately this game can also be adapted to an application in the private sector like it is the case for the climate collage that is often being used as a "team-building" tool. Some companies, especially the one that can have an impact on soils may be interested in offering their employees a workshop on soil and soil health. We will be doing our first test-sessions to companies such as Unilever, Nestle and Danone.

6. What does it mean for Horizon 2027?

The creation of a serious game could be a deliverable. The advantage of board serious games is that you can easily modify them, create more expert versions for different public.

It is a communication format that can be sent to the whole European Union while remaining adapted to the local context. In fact, in each country, the cards will be translated, and the trainers will speak the local language. The game can be adapted to different levels of knowledge but also to different contexts. For example, if a region faces a dramatic soil erosion problem, this aspect can be highlighted during the workshop. It is a flexible and easy to organize means of communication. It is both global and local. It empowers soil health stakeholders but also citizens: after three hours, everyone leaves with a concrete idea of 1- how the soil functions, 2- how the humans impact this functioning, 3- what one can personally implement in his daily life related to soil health.

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Annexes

Annexe 1

1. Game

General

The game is expected to last 3 hours.

Phase I

Players are using the “actor cards”. Each round, every player gets one card. Each after another they are asked to show the card in their hands and to place it on the board. Once the card is on the board, it needs to be connected via arrows. The players can think together how to link the card to the other ones on the board. In case they have no idea, the trainer can help them by explaining some scientific facts. At the end of this phase, the player has a basic knowledge of the soil functioning in a natural ecosystem from a biological, physical and chemical point of view.

Card “Plant/Dead plant”

I. What does a plant need to grow?

Card “Sun”

II. What is photosynthesis? **Plants** make food in their leaves. The leaves contain a pigment called chlorophyll, which colours the leaves green. Chlorophyll can make food the **plant** can use from carbon dioxide (CO_2), water and energy from sunlight. This process is called photosynthesis. However, they cannot transform CO_2 into Nitrogen and Phosphorus, which they also need for a healthy diet.

Card “Nitrogen (soil)”

III. What is Nitrogen?

IV. Where does the nitrogen come from?

Card “Micro-fauna/ Dead micro-fauna”

V. Who is the micro-fauna (some examples)? What do they eat? The micro-fauna (earthworms for example) need to eat. They eat dead plants which bring the plants back to the soil, and ready to be eaten by Bacteria and Fungi.

Card “Dead plant in little pieces”

VI. Who is decomposing the plants? Who eat them?

Card “Bacteria/Dead Bacteria” + Card “Fungi/Dead Fungi”

VII. What is mineralization/immobilization? Bacteria and Fungi eat (thanks to special enzymes they can eat from the dead organic matter= dead plants). When they get energy from dead plants they transform the dead plants back to nutrients (Phosphorus, Nitrogen) that plants can eat (assimilation), water and Carbon (CO_2).

Card "Nodules"

VIII. What is nitrogen fixation?

Card "Phosphorus (soil)":

IX. Where does the phosphorus come from?

Card "Rocks"

X. What is weathering?

Card "Mycorrhizae"

XI. What is a mycorrhiza? Some Fungi are friends with some plants. Mycorrhizae are providing water and nutrients (Nitrogen, Phosphorus) from the soil or the rocks to the roots of the plants. More than 80% of plants have Fungi -friends

Card "Clay/Oxides"

XII. Why is the phosphorus in the soil sometimes unavailable?

Card "Water (soil)"

XIII. Where does the water come from?

Card "Rain"

XIV. How does the rain enter the soil?

Card "Pores" & Card "aggregates"

XV. What is soil structure? How does the soil structure influence the water entering in the soil?

Card "Channels"

XVI. Who are creating those channels?

<u>Phase II</u>

For the second phase, players get some "human-induced actions cards". Each round, every player gets one card. Each after another they are asked to show the card in their hands and to place it on the board. Once the card is on the board, they must understand on which process talked about before it has an influence. By the end of this phase, the player understands how humans influence soil functioning through agricultural practices. Those cards can be placed in a different order than the one offered below, according to the players' inputs.

Card "Food/Clothes/Fuel"

I. Why do plants matter for humans?

Card “Crop selection”: humans select what they want to eat, introduction of monocultures

II. What influence does it have on the natural functioning of the soil?

Card Deforestation

III. What influence does it have on the natural functioning of the soil (especially on the soil carbon)

Card “City life” (Urban area building)

IV.

Card “Kill your enemies” (pesticides)

V. What are pesticides? Why and when were they introduced ? How do they influence the soil functioning and the plant production?

Card “Speed up your soil” (increased tillage)

VI. What is tillage? Why and when were they introduced? What are the benefits and disadvantages or it?

Card “Faster and easier” (Machineries)

VII. Why are machines necessary in an agricultural system? How does it affect the natural functioning of the soil?

Card “Extra-food” (animal manure)

VIII. Why to put animal manure on the soil? What impact does it have on the soil functioning?

Card “Extra-food”

IX. Where does the Nitrogen fertilizer come from? Explanation of the Harber-Boser process.

X. Where does the phosphorus fertilizer come from?

Card “Extra-water” (increased irrigation)

<u>Phase III</u>

In the last phase, the plays get the cards “consequences”. Again, each round, every player gets one card. Each after another they are asked to show the card in their hands and to place it on the board. Once the card is on the board, they must understand on which process talked about before it has an influence. By the end of this phase, the player understands how the agricultural practices induced by humans influence not only the functioning of the soil but also the functioning of the ecosystem as a whole.

Card “Air, water & soil pollution”
Card “Overload of nutrients in the soil: Emissions”
Card “Overload of nutrients in the soil: Leaching”
Card “No diversity (time and space): built-up of pathogens”
Card “Breakdown of aggregates: CO2 emissions”
Card “Water runoff/flooding”

Card “Soil erosion”
Card “Soil salinization”

2. Game cards

<u>Actors (22)</u>

- Plant + Bacteria-friend = nodules
- Dead plant in little pieces
- Plant/ Dead plant
- Food/Clothes/Fuel
- Water (soil)
- Phosphorus (soil)
- CO_2
- Air
- Rain
- N_2O
- N_2
- Sun
- Phosphorus (soil)
- “Bad guys” (Pathogens)
- Micro-fauna/ Dead micro-fauna
- Fungi/Dead Fungi
- Bacteria/Dead Bacteria
- Plant + Fungi-friend = mycorrhizae
- Soil engineers
- Nitrogen (soil)
- Rocks
- Clay/oxides

<u>Human-induced actions cards (9)</u>

- Card Deforestation
- Card “City life” (Urban area building)
- Card “Kill your enemies” (pesticides)
- Card “Speed up your soil” (increased tillage)
- Card “Faster and easier” (Machineries)
- Card Crop selection (humans select what they want to eat, introduction of monocultures)
- Card “Extra-food” (animal manure)
- Card “Extra-food” (fertilizers from mines or from Harber-Bosh process)
- Card “Extra-water” (increased irrigation)

<u>Consequences (8)</u>

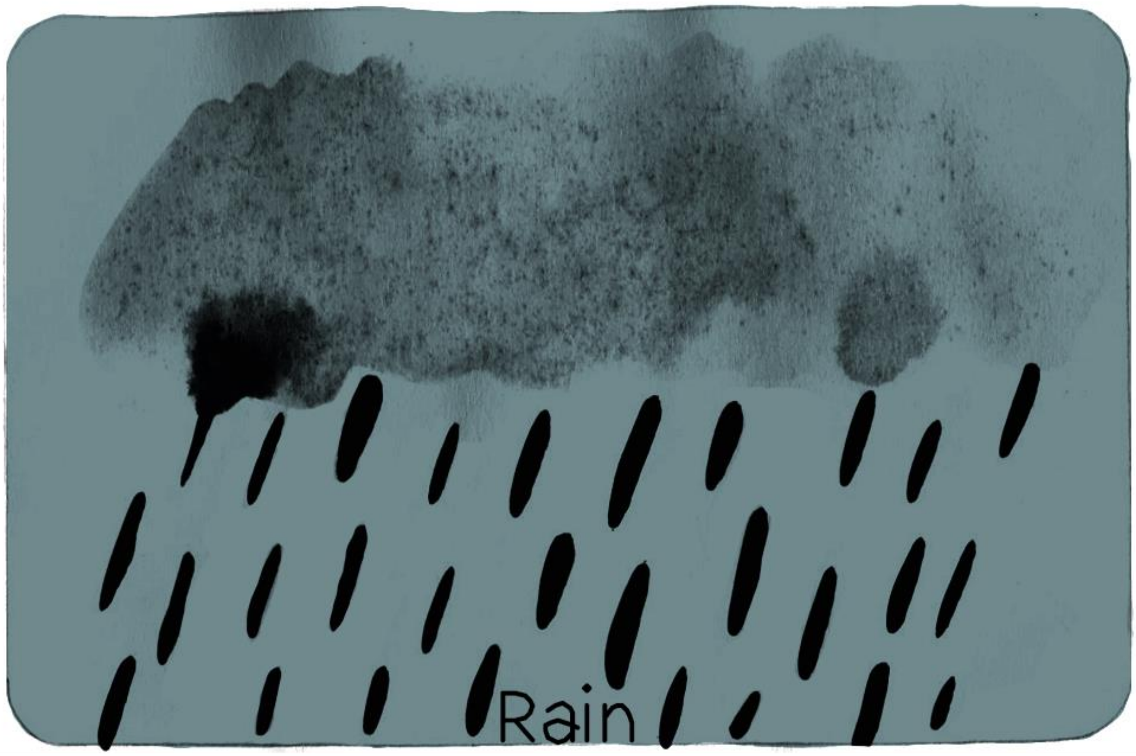
- Air, water & soil pollution
- Overload of nutrients in the soil: Emissions
- Overload of nutrients in the soil: Leaching
- No diversity (time and space): built-up of pathogens
- Breakdown of aggregates: CO_2 emissions

- Water runoff/flooding
- Soil erosion
- Soil salinization

Arrows (4)

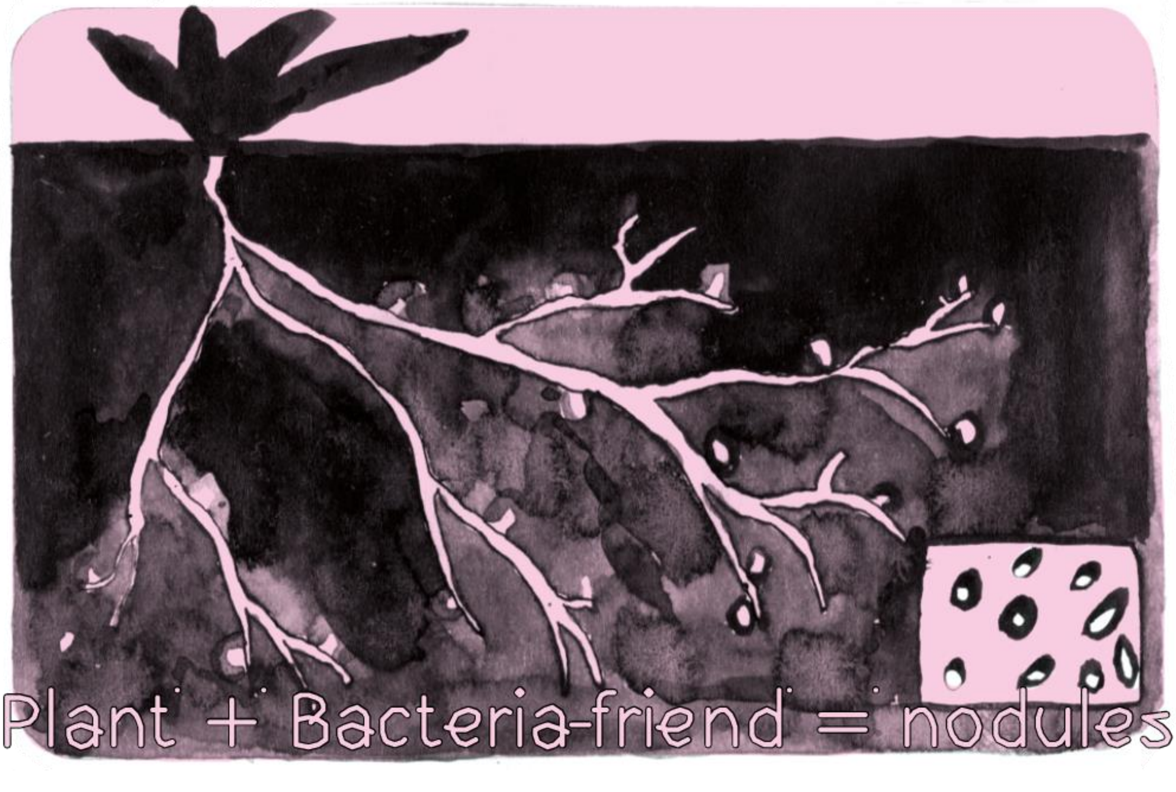
- Production
- Ingestion
- Excretion
- Symbiosis

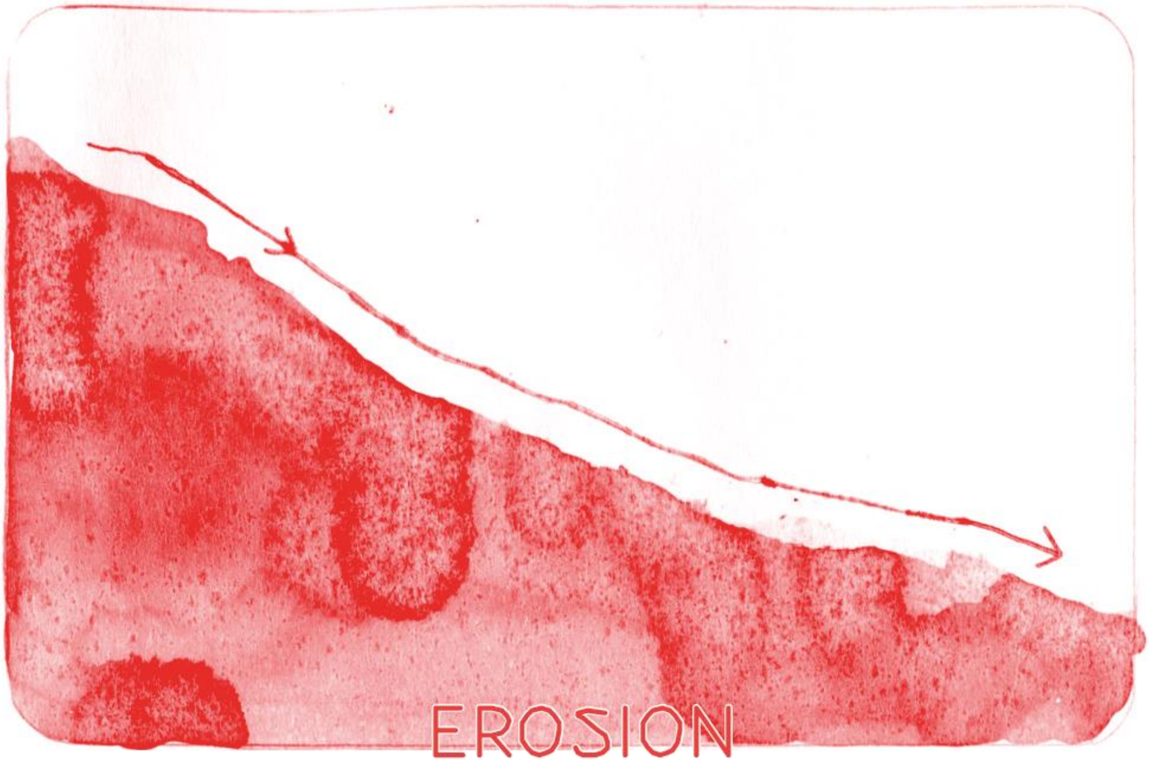
3. Some examples of cards


Rain

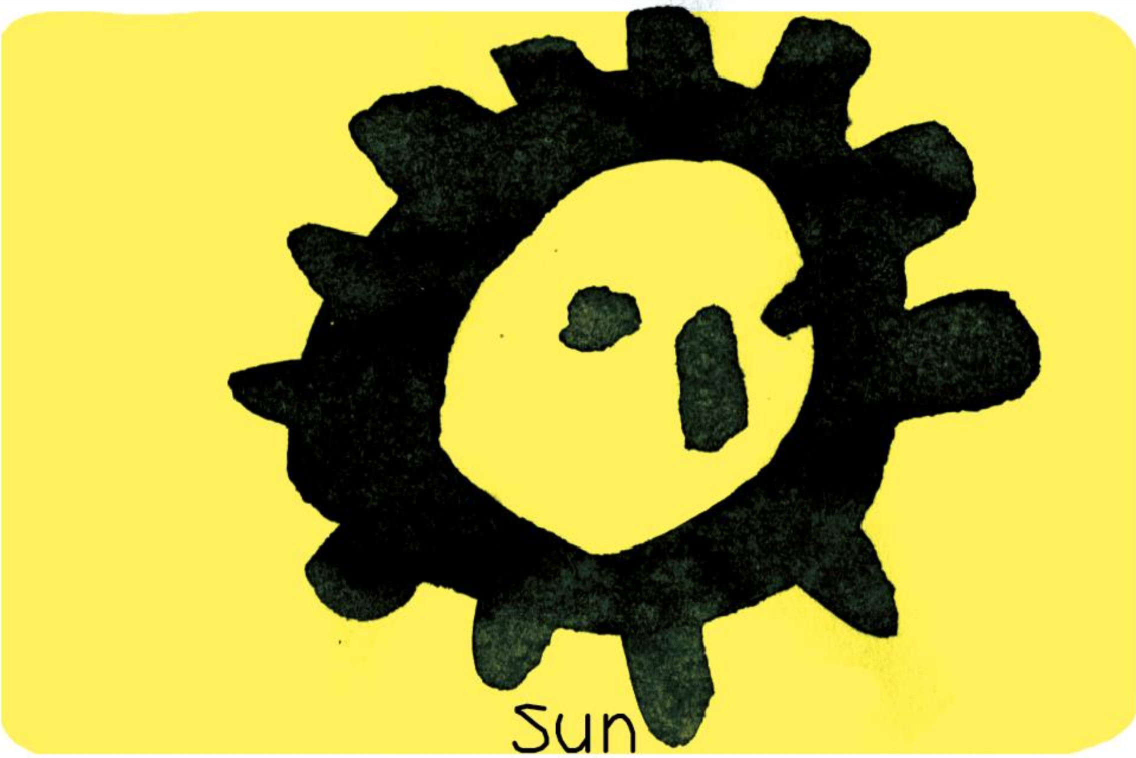

Plant/Dead plant


"Bad guys" (pathogens)


Plant + Bacteria-friend = nodules


EROSION


LEACHING



Plants make food in their leaves.
The leaves contain a pigment called chlorophyll, which colors the leaves green.
Chlorophyll can make food the **plant** can use from carbon dioxide (CO_2), water and energy from sunlight.
This process is called photosynthesis.