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A nation that rebuilds its soils rebuilds itself- an engineer's perspective

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ABSTRACT

Nations can build and rebuild degraded soils to help address climate change and potentially improve the nutritional content of food if we change policies that allow the addition of safe mineral and organic wastes to soil. We present a framework that facilitates the transition from intensive conventional to more regenerative farming practices by considering soil's natural cycle. Our paper is presented in three parts. Firstly, we consider that 'soil is living'; just like humans, the soil biome needs a balanced diet of macro and micronutrients as well as a nurturing environment. We simplify the soil science and take a systems approach which focuses on restoring soil's natural cycle to benefit both health (by increasing micronutrients in soil) and wealth (through climate change adaptation and mitigation). Secondly, we consider the scale of the problem of soil degradation and the timescales involved in rebuilding soils and barriers to implementation. Thirdly, we propose a potential framework which enables communities to identify what might be missing from soil's natural cycle. This framework helps communities consider how they might change soil texture by addition and manipulation of both minerals and organic matter. We present an educational tool, 'soil in a jar' based on a narrative of nurturing soil which is designed to engage and inspire society to get their hands dirty. Communities can use the framework to produce locally specific solutions to restore their soil's natural cycle and rebuild their local and national economies.

1. Introduction

Engineers, working with scientists, social scientists and educators must help communities to build new soils and rebuild degraded soils. We propose a core framework targeted at engineers to work with communities and scientists to consider whether we are taking more materials out of soil than we are putting in, that is if something is missing from soil's natural cycle. Ostrom and Nagendra (2006) showed that giving communities scope to dictate the rules is important in managing shared resources. Our framework aligns with the UN's Sustainable Development Goal 15.3 on sustainable terrestrial ecosystems as well as with more regenerative (meaning enhancing soil health) agricultural practises. Roosevelt said "*a nation that destroys its soils destroys itself*". This truism came out of the bitter economic and social devastation caused by agricultural practises that did not acknowledge that soil is a living system with material and energy input requirements. Soil was literally blown away in the 'Dust Bowl' of the US Midwest in the 1930s. Our framework which considers soil at a local ecosystem scale and the site-specific availability of both organic and inorganic materials which might be needed to rebuild soils re-frames Roosevelt's original quote into a more constructive perspective. We propose that "*a nation that rebuilds its soils rebuilds itself*".

Importantly the framework allows for a spectrum of measures to improve soil health, from nurturing to rebuilding and even building

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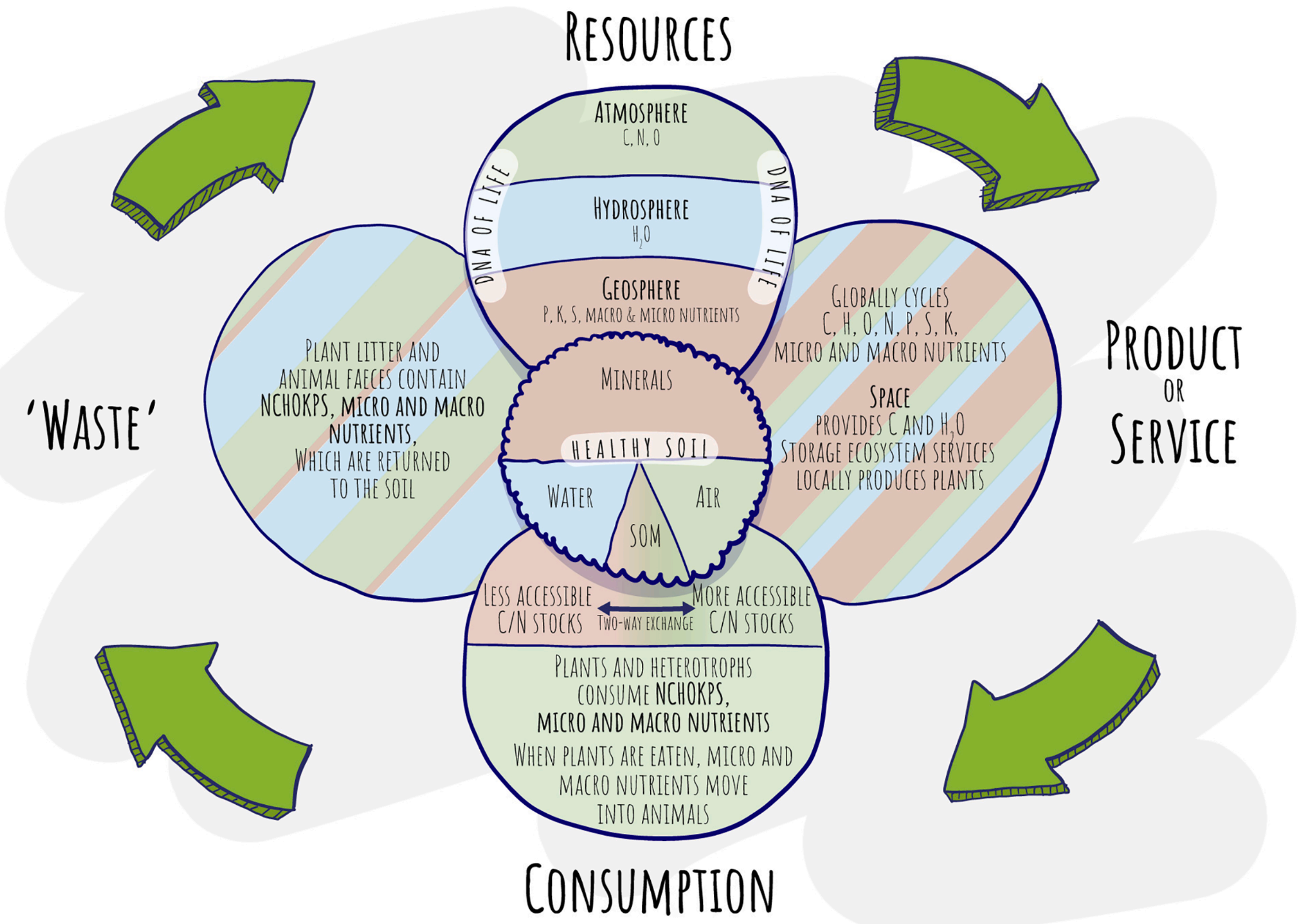

Figure 1. Soil's natural cycle – shown as a "circular economy" with Resources - Product/Service - Consumption -Waste. Note that colour scheme designates whether the resources or materials come from the hydrosphere (blue water), atmosphere (green air), or geosphere (brown minerals) with SOM having both blue, green and brown components representing more accessible (green) and less accessible (brown) carbon stocks.

from scratch. By soil health we mean the 'condition' of the soil (one of the 5 Cs of McBratney et al 2014). Nurturing might simply involve using fewer chemicals so that the soil can return to its natural cycle. The 'rebuild' conceptual framework is predicated on the ability of local communities, advised by scientists and engineers to improve soil health by adding organic matter and inorganic minerals of certain particle size and composition so that soil structure can be optimised for both carbon and water storage. The addition of inorganic minerals to soil may also provide missing micronutrients to the benefit of human health. Waste materials must be clean and ideally locally available which will mean in many cases urban and peri-urban soils will be easier to rebuild. However if we are to address global challenges such as food security, land degradation and climate change before 2030 or even 2050 (Smith et al 2021), we need to change the economic and legal structures that are holding us back from rebuilding rural soils. We highlight the urgent need for 'codification' (one of the 5 C's from McBratney at al 2014) that is for policy-makers to allow engineers to play a full part in rebuilding degraded soils (Johnson et al 2016) by reclassifying clean 'wastes' to by-products for use in both urban and rural soils. We briefly discuss key relevant socio-economic issues a community must consider if they are to succeed in rebuilding soil health by restoring soil's natural cycle. We focus on the links between soil health (UN Sustainable Development Goal 15) and education (SDG4), the sustainable use of wastes (SDG12) and on climate change (SDG13). Our framework and proposed 'soil in a jar' educational tool increase 'connectivity' (one of the 5 Cs of soil health from McBratney et al 2014) between stakeholders by simplifying the complexity of soil science into a narrative that stimulates an accessible (and rigorous) philosophy of care, through community engagement at every level (Dominelli, 2012).

2. Soil is living

There has been growing evidence over the last few years for the fact that as opposed to "soil has a living component", that "soil is living" and acts as an extended composite phenotype (eg Neal et al., 2020) helping to build the soil architecture. Just like a bird's genes control its nest architecture or a beaver's genes control the landscape architecture resulting from its activities, the soil biome controls soil architecture below ground. Much of Earth's biodiversity is in the soil. It follows that a healthy living soil with a good soil architecture engineered by its biome provides the ecosystem services needed to support terrestrial ecosystems (Bardgett and van der Putten, 2014, FAO et al. 2020). Soil is, therefore, the foundation of our collective human health (e.g. Brevik et al., 2020) and wealth as Roosevelt neatly articulated nearly 90 years ago. And yet we now know that through our extensive use of pesticides and herbicides in our conventional intensive agricultural systems, we have killed much of this life (Gunstone et al., 2021). We also know that with our overuse of chemical fertilisers we have significantly damaged the symbiotic relationships between the plant and soil microbiome (Jacoby et al., 2017).

Soil is the largest biospheric store of organic carbon on Earth (Trumbore, 1997). Soil organic matter (SOM) is not homogenous in terms of its elemental composition but roughly 50% of it is carbon. SOM can be seen as a spectrum of more or less accessible 'pools' or stocks (see Figure 1) (Lehman and Kleber, 2015). Both pools ultimately come from the atmosphere via photosynthesis with the more accessible 'active' pool having a faster turnover as a source of energy and materials for the soil biome and ultimately for terrestrial life. The less accessible form is harder for the soil biome to access either because it may be either: inherently enzymatically difficult to degrade (albeit not completely refractory), far removed from oxygen (either trapped within soil aggregates or in present in anoxic zones) or chemically bound to mineral surfaces (Six et al., 2006). The less accessible form is important because it is part of the glue which holds soil minerals together and helps maintain the soil structure that supports terrestrial ecosystem services (Baveye et al., 2016).

Since industrialisation began, the one-way (linear as opposed to circular) utilisation of Earth's resources including soil has resulted in human activity becoming a dominant cause of global environmental change (Lewis & Maslin, 2015) including soil degradation and habitat loss. A move from our current linear to a circular economy requires us all to change our lifestyles and diets, as well as move to more sustainable agricultural practices. Soil, having been the Cinderella of resources, must become an integral part of that circular economy as it is increasingly understood to underpin all of the UN's Sustainable Development Goals (Keesstra et al., 2016, Evans et al., 2021, Smith et al 2021). These seventeen goals encapsulate many of the socio-economic and environmental and sometimes conflicting issues that we must tackle/resolve to integrate our circular economy with soil's natural cycles.

We do not review the various physical, chemical and biological facets of soil which contribute to its health. Although there is no consensus, soil health (or condition) is often defined as the ability of soil to deliver essential ecosystem services a subset of which includes food security and climate change adaptation and mitigation. Indeed, due to the complexity of soil and soil organic matter (SOM), there is still disagreement on how best to maintain and enhance soil health and even disagreement on how SOM is formed and preserved (Lehman and Kleber, 2015). Soil health is a multi-faceted and complex term just like human health. We care about human health and we need to care about soil health as the two are intrinsically linked for example through micronutrient provision (e.g. Platel and Srinivasan, 2016). There is however a consensus that SOM underpins soil health (e.g. Voltr et al., 2021). And, we know that more regenerative land management promotes soil health and that our conventional intensive agriculture is harmful (Borelli et al., 2017).

The need to feed soil with organic matter and add minerals at the field scale to improve soil structure has long been understood. Our approach to building and rebuilding soils differs only in that we propose that because 'soil is living' as opposed to having life in it, it can rebuild itself if we restore its natural cycle (see Figure 1). We define a healthy soil microbiome, which is arguably the foundation of a healthy soil, as one that "*maintains a high diversity of functions across a range of organisms having as broad a range of traits as possible*". Moving beyond the natural soil cycle, we can engineer soils to enhance carbon storage and improve micronutrient content of our food by adding minerals to feed the microbiome. Evidence shows that (i) plants use root exudates to "construct" their root microbiome (Balasubramanian, 2021), (ii) reciprocally plant microbiomes enhance plant nutrient acquisition and growth (Carvalhais et al., 2013), and (iii) plant microbiomes improve plant adaptation to environmental stress (Yandigeri et al., 2012; Symanczik et al., 2018; Carlson et al., 2020) and confer or enhance defence against pathogens (Cha et al., 2016; review by Finkel et al., 2017). Plant breeding and genetic modifications without contact with the soil microbiome can therefore have negative impacts on the health and resilience of crops (Parnell et al., 2016). Therefore, placing soil health and restoring soil's natural cycle in agronomic and pest management systems (e.g. Deguine et al., 2021) could provide climate-resilient food security; as well as positive outcomes for both climate change mitigation (reducing global greenhouse gas emissions) and adaptation (storing both C and N in soil) as explained in the section on climate change (SDG13, section 8.2).

Soil is of course highly variable and affected by climate, geology, landscape processes and time (Jenny, 1941). Van Breemen (1992) sums it up by saying "*soils derive their existence from life processes on a global scale, and are made more fit for plant growth by life processes on the ecosystem scale*". But broadly, soils contain 4 non-living parts as well as the living micro and macrofauna and flora: 1) inorganic minerals; 2) non-living organic matter; 3) air and 4) water.

A natural cycle or "circular economy" in nature is one where inputs and outputs are balanced, and can be seen as sustainable. Globally, soil's natural cycle provides functions that deliver ecosystem services. Soils are essential in helping regulate global macro and micronutrient biogeochemical cycles like the C and H_2O cycle as shown in Figure 1. Locally, soil functions like food production and water storage have been important to humans for millennia. But soil has generally been undervalued by society.

We have broken soil's natural cycle (Figure 1) in significant proportions of our cultivated agricultural land through land mismanagement and intensive agricultural practices (Borelli et al., 2017) which have had both local (eg micronutrient deficient food) and global effects (e.g. imbalance of global greenhouse gas emissions through release of N_2O emissions in intensive agriculture). Neal et al. (2020) suggest that once soil no longer has the inputs of accessible 'active' carbon as an energy source it is no longer able to self-organise and help build soil architecture; it then tips into a disorganised 'critical' state. Once not able to self-organise, soil will no longer be soil, but a pile of minerals with scant organic matter. This pile of minerals with insufficient organic matter will no longer be able to deliver the ecosystem services including provision of micronutrients in our food which are important for human health. But Neal et al. (2020) also suggest that soil can recover from the critical state once the input of accessible carbon is restored. We suggest that in addition to carbon, minerals are needed in many cases because in many degraded soils, as micronutrients are also rate-limiting (and therefore ecosystem service-limiting).

The sustainable raw materials for a healthy soil microbiome include accessible carbon which is used as an energy source via microbial respiration, but also many other macro and micronutrients provided by a mixture of both organic and inorganic materials. Figure 1 shows that soil in the terrestrial biosphere is made of materials (C and N) and energy (C) which are sourced from different 'reservoirs': the atmosphere (shown in green, via primary productivity and N fixing bacteria respectively), the hydrosphere (shown in blue) and the geosphere (shown in brown). But humans have altered soil's natural cycle by preventing inputs of these materials from those 'reservoirs' for example by leaving soil fallow and redirecting and banking rivers. These and other changes can result in soil degradation, via losses in SOM build up and decreases in soil health. Restoring this balance of material inputs is essential in any framework. We propose a core framework to promote restoration of this 'circular economy' for soil. Communities who wish to rebuild their soils must take into consideration on a case-by-case basis what is missing from their soil's natural cycle and then assess which site-specific material inputs of both organic and inorganic materials (e.g. minerals) can be made available. Bioavailable micronutrients (e.g. Fe, Zn, Iodine and Vitamin A) are commonly now missing from the soil and are therefore missing from human diets (Platel and Srinivasan, 2016) particularly in the global south. Involving women in community initiatives aimed at rebuilding soils is crucial to maintaining soil (and human) health as they are key contributors to agricultural production in many societies (Zhang et al., 2017). This is our starting point for why we need to rebuild soils and why we must focus on ensuring the soil microbiome has access to micronutrients as well as macronutrients.

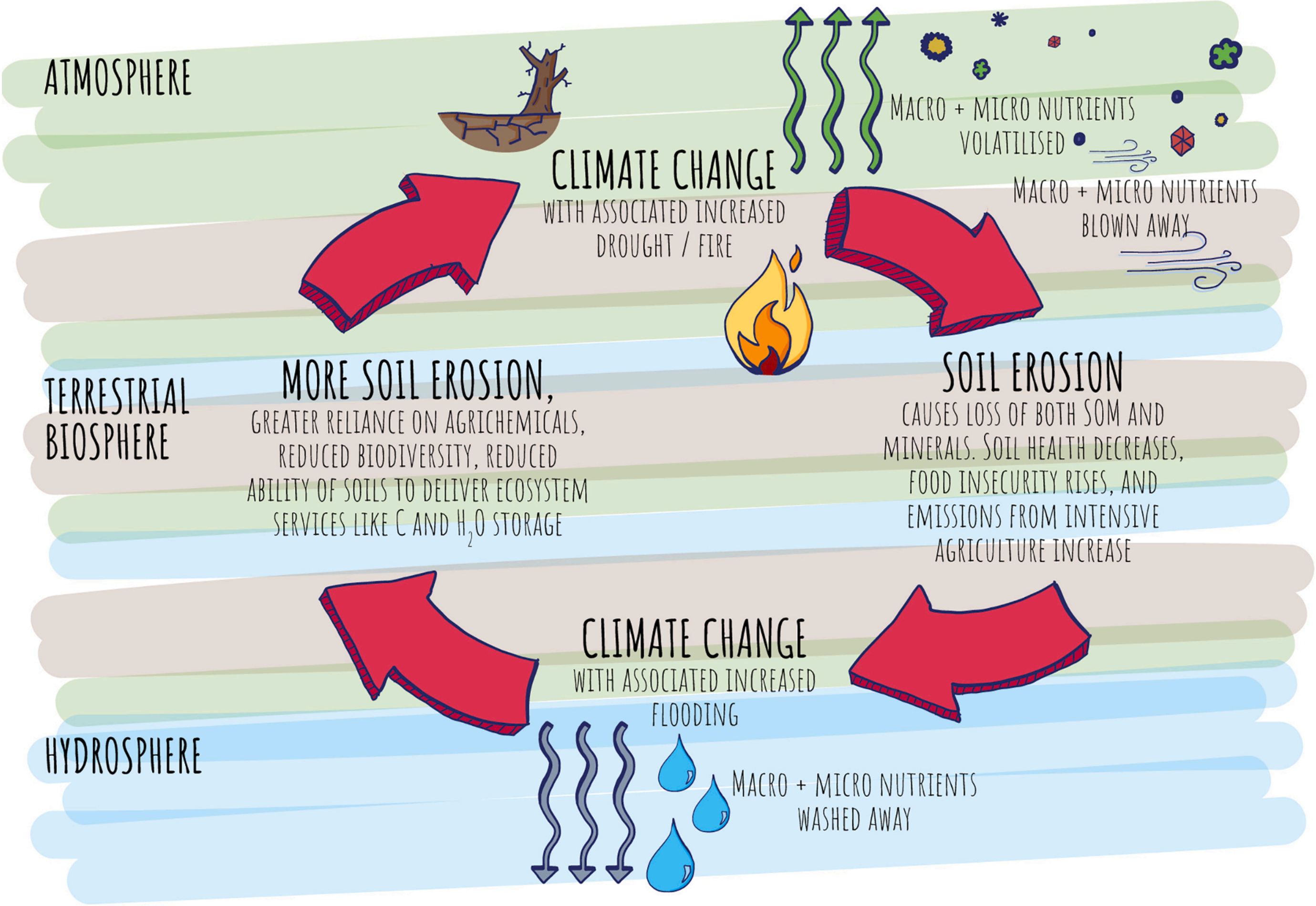

Figure 2. Vicious cycle of soil degradation and climate change - where the already degraded soil (due to land mismanagement by communities and intensive agricultural practices) is in a negative feedback loop with the extreme flooding and drought/fires caused by climate change. Both organic and inorganic components of soil are literally washed away under flooding, blown away under drought and damaged under severe wildfires which can contribute to greenhouse gas emissions. However, the biggest link between soil degradation and climate change is that soil degradation leads to overuse of agrochemicals in conventional intensive agriculture which not only directly feeds global greenhouse gas emission but further decreases soil biodiversity, exacerbating soil degradation and increasing soil's vulnerability to the extremes of flooding and drought/fire.

3. How we got here - the vicious cycle

We continue to treat soil as an externality in our linear industrial economy by not measuring or valuing soil health. We must produce reproducible methods for measuring soil health (Wander et al., 2019, or even produce robust definitions of exactly what soil health is). But we already know enough now, especially what soil health isn't, to start rebuilding soils. Soil degradation has occurred because we have used soil to produce food through conventional intensive agriculture and in doing so we have broken soil's natural cycle. Our increasing reliance on fossil-fuel derived agrichemicals to make soil productive has created a vicious cycle between climate change and soil degradation as shown in Figure 2.

One example where we have significantly disrupted or completely broken soil's natural cycle is where soil is unvegetated (see Figure 3). Soil without plants has reduced microbial diversity and diminished functional capacity when compared to vegetated soil (Kushwaha et al., 2020; Zeng et al., 2020). Without plant root networks soil becomes loose and vulnerable to wind erosion during drought. Droughts also directly impact the soil biome. Studies covering all continents (except Antarctica) determined that prolonged/permanent drought reduces the abundance and diversity of soil bacteria and fungi (Maestre et al., 2015; Neilson et al., 2017), which impacts nutrient cycling and sequestration of carbon (Zhou et al., 2011; Triverdi et al., 2013). However, natural soil systems which are largely dependent on fungi for carbon and nitrogen cycling are more tolerant to drought than intensive agricultural systems dependent on bacteria for soil carbon and nitrogen cycling (de Vries et al., 2012). In addition, there is growing evidence that the soil microbiome plays a significant role in plant drought stress-adaptive responses (de Vries et al., 2020). Thus, climate change and droughts are likely to have disproportionately more devastating impacts on conventional intensive agricultural crop production by affecting soil health, when compared to more natural soils. Another example of the broken natural cycle for soil is how we have separated livestock and arable farming – we point the reader to reviews that consider the opportunities for integrated arable and livestock farming (Knight et al., 2019).

The use of chemical N in conventional intensive arable farming, although improving crop yields for many years, also has a role to play in Figure 2. Overuse of chemical N has changed the C:N ratio in soils. As well as directly increasing global greenhouse gas emissions via N_2O release, the use of chemical N has also removed the incentive for symbiotic collaboration between legumes and nitrogen-fixing bacteria (Henson and Bliss, 1991). Chemical N application also reduces microbial biomass (Treseder, 2008; Liu & Greaver, 2010), which may disrupt stress-adaptive responses conferred on plants by rhizosphere microbes (Xu et al., 2018). Chemical N use may be working against our attempts to enhance carbon storage in soils since carbon storage is positively correlated with microbial activity and biomass generation (Zheng et al.,

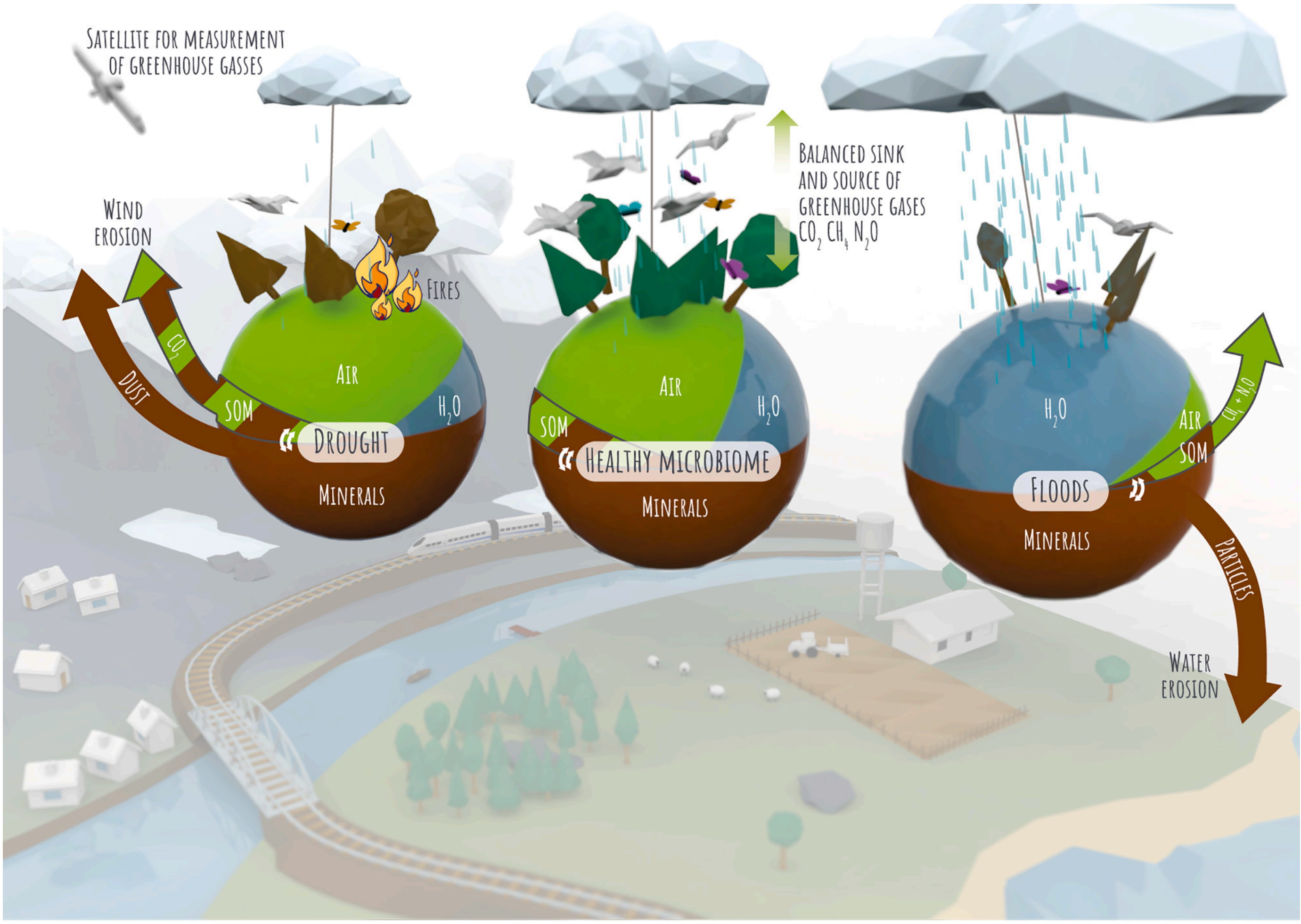

Figure 3. Healthy soil has a 'circular economy' where inputs and outputs of C and N and other macro and micro nutrients are balanced. SOM is central to the living soil. Many soil functions and SOM turnover and production of the GGH CO_2, CH_4 and N_2O is/are related to both water content and redox, both of which are related to soil structure. We highlight here the role of minerals in SOC stabilisation (one of the key controls on SOC accessibility) and therefore soil structure, as well as the circle of SOC degradation and climate change represented by the Newton's cradle configuration representing the link between healthy soil (centre where soil has natural cycle of balanced inputs and outputs – see Figure 1) and degraded soils (as represented by more outputs than inputs of both solid particles and gases) under extreme drought (LHS) and flood conditions (RHS) caused by climate change. The satellite represents future soil health data collection via satellite technology.

2019). Extending the same thinking, there is a need to understand the effect chemical N has on the biome's ability to weather minerals, if the use of chemical N has affected this then as well as degrading soils we are potentially actively slowing down natural pedogenic processes.

Inputs and outputs of both carbon and nitrogen are out of balance and it is generally acknowledged that cultivated soils are carbon-limited (Demonling et al., 2007). The changes to both the N and the C cycle working against soil's natural cycle has created poorer soils with reduced capacity for self-regeneration and stabilisation.

Overall this general lack of carbon inputs means soils, as living systems, do not have the inputs of energy and materials they need, which, alongside compaction (see tractor in Figure 3) has damaged the biome's ability to help build soil architecture. Our widespread modification of the landscape alters flow regimes and the natural terrestrial cycling of carbon and other macronutrients (Lin, 2010; Doetterl et al., 2016). We have also changed the input of water to the soil in both arable and urban systems either by use of irrigation from frequently over-extracted groundwater supplies or sealing the surface of severely compacted or dispersed soils. Many excellent reviews cover these macronutrient cycles (e.g. Zhu et al., 2017) but to the authors' knowledge no-one has considered how alteration of the supply of micronutrients to soil has affected soil health. By either cutting or significantly changing the input of inorganic minerals to the soil and by changing the hydrology and/or sediment flow by channelling river systems and building of reservoirs we have broken soil's natural cycle of micronutrients. In many cases we take out more micronutrients than we put back into our cultivated land. In the global north we bypass the soil by using precious mineral resources to manufacture nutrients for fortification of our food and take vitamin supplements.

On a global level, as climate change continues to increase the frequency of flooding and drought and fire, there is an urgent need to put in place a framework that converts the vicious cycle we are in, to a virtuous cycle. Restoring soil's natural cycle by rebuilding soils with minerals and organic matter helps us deliver the UN's 17 SDGs but specifically will help address goals SDG2.2 (ending micronutrient-related malnutrition), SDG2.4 (resilient agricultural practices which maintain ecosystems) and SDG15.3 (restoring degraded land).

4. How to make good - the virtuous circle

We propose to change the vicious cycle into a virtuous one by building (in cases where there is no soil) and rebuilding or nurturing (where soils are degraded) soils to have as close to a natural cycle as possible. Indeed, in some cases we might want to move beyond that natural cycle, engineering a new soil that provides the relevant ecosystem services for today. These ecosystem services will vary between communities but might include increasing micronutrient content of food and mitigating climate change aligning with the '4 per 1000′ initiative resulting from the Paris UN COP21 commitments (Minasny et al., 2017). We hope that by simplifying the science into a framework that enables communities to act locally to restore soil ecosystem services there can, over time, be positive global impacts. Climate change has happened because of many both small and large emissions of carbon into our atmosphere and over the next 30 years climate mitigation, we will need to implement many both small and large strategies to stop emissions, if we are to achieve net zero and to restore biodiversity by 2050.

When agricultural practices work with soil and treat it as a living system that has material and energy requirements to survive we will have succeeded in moving from the vicious to virtuous circle. Living systems, just like humans, require inputs of accessible carbon (which provides a source of energy) as well as less accessible more 'stable' carbon (which helps build structure) and other macro and micronutrients (the materials from which living materials are built). We do not 'build' our children: we feed them the right diet of carbon, nitrogen and minerals and allow their DNA to do the rest, although it does take time to grow a human, around 20 years. We simplify the science for engineers who can see the energy and materials – the diet that soil needs - as inputs and outputs and we can reduce these to four rudimentary components: 1) the minerals, 2) the organic matter, 3) the air and 4) water.

We propose a narrative of caring about soil health in the same way as we care about human health. There is mounting evidence for links between the soil biome and human health (Wall et al., 2015) and also increasingly for direct links between soil health and our gut microbiome (Blum et al., 2015). This easy to comprehend analogy between human health and soil health is our starting point for how to engage society in the 'rebuild soils effort'. For this reason, we propose an educational philosophy of nurturing the soil like we nurture our children which has the potential to connect people with soil throughout their lifespan, whatever their profession. But first we need to consider how long this will take, at what scale is this achievable and what needs to change in order to implement this change.

5. How big is the problem?

Estimates vary, but around one third of all global soils are degraded (UNEP, 2015). Looking at the 104 million km^2 of habitable land in the world (this area excludes glaciers and barren land), ~50% is used for agriculture (51 million km^2). Of this agricultural land, globally, 77% is pastureland used for grazing livestock and 23% is used for arable farming. Soil degradation has generally either been caused by mismanagement of land (eg tilling) or intensive agricultural practices (Borelli et al., 2017). It is estimated that of this agricultural land, ~24% is degraded, affecting 1.5 billion people (UNEP, 2015). Urban soils are also often degraded and also provide ecosystem services which could be improved. However urban and rural soils have for too long been treated as separate entities when in fact in many cases there is a continuum between them. Wherever there are minerals, organic matter, air and water there is soil. This paper aims to build a bridge between urban and rural soil academic and practising communities and a bridge between engineers and scientists.

Soil degradation is often characterised by a loss in SOM which has knock on effects for both carbon and water storage and biodiversity. Decreasing levels of SOM lead to soil becoming more vulnerable to extreme weather events (Kumar & Das, 2014). Global soil degradation is a problem for many different land use and soil types but we only consider cultivated soils in this rebuild framework. Approximately 44% of cultivated agricultural land exists in dryland areas where soils are particularly vulnerable to degradation and particularly to acidification and salinization with this figure set to increase because of climate change. There are many excellent reviews of the importance of SOM to soil health (Lal, 2016) but there is less information about the importance of inorganic minerals in soil health.

Minerals are being removed from soil faster than they are being replaced. Finer clay sized particles are often carried away (via air, fire or water) in floods, droughts and fire (Fig 2). Even in resilient soils where minerals are not lost in floods or droughts, minerals are constantly removed when food, textiles and bioenergy crops are harvested and, in some cases, either due to aged soil (eg in tropics) or changes in hydrology and sediment flow, the biome (and therefore plants and also humans without access to vitamin supplements) can no longer access essential micronutrients. In these cases, we can consider how to restore access, either by addition of pedogenic or waste minerals (see section 7.1). Micronutrient deficiency is a problem all over the world (eg Platel and Srinivasan, 2016) but arguably greater in many developing countries (eg Manzeke et al., 2012) where tropical soils are older and have already been 'mined' by the microbiome and plants. Work conducted in Zimbabwe indicated that zinc (Zn) deficiency was prevalent in >80% of surveyed smallholder farms (Manzeke et al., 2014).

One barrier to returning mineral and organic wastes to soil is current policy and legislation. National and international legislative frameworks can contribute positively to the establishment of a circular economy (see section 8.2), and the reclamation of waste materials to rebuild soils. In the EU this takes the form of the Waste Management Directive (Directive 2008/98/EC), where disposal of material to landfill is the least favoured and most expensive option. This encourages the diversion of a large amount of inert and biodegradable waste away from landfill so that it can be reused as a by-product. However, reclassification of 'wastes' to by-products is laborious and there is an urgent need for national circular economy policies to reclassify clean safe mineral 'wastes' as by-products which can be used in agriculture. There are some success stories of policy implementation at scale. For example, in Brazil, the Rochagem movement has provided a legal framework for using silicate rocks to add macronutrients (applications every 4-5years) to their limestone-based soils with impressive results including reducing costs of chemical fertiliser use by 80% (Manning et al., 2020).

6. Building and rebuilding soils

We can build artificial soils (technosols) using mineral and organic waste materials and optimise them for agriculture (Koolen and Rossignol, 1998). Evidence seems to suggest that the time taken for performance to be on a par with natural soils varies but is around 5-20 years. In SE Brazil, reconstructed soils made from limestone spoil and placed under sugarcane (2-7 years) and pasture (20 years) revealed soil quality indices (including biodiversity) that were similar or superior to adjacent natural soils, while the total carbon stocks in the reconstructed soil under pasture were 2.7 times higher (Ruiz et al., 2020). In northern France, soils were constructed from thermally-treated industrial soil, papermill sludge and green waste compost, and planted with grasses; over 12 years, total organic C stocks in these reconstructed soils were up to 5 times higher than in natural analogue soils (Rees et al., 2019). Schofield et al. (2018) studied an organic-rich reconstructed soil comprised of green waste, composted bark, sand and clay from a visitor attraction in SE England, UK, which houses a diverse ecosystem containing thousands of plant species from around the world. N-retention was in the range expected for natural soils, but the soils appeared to be vulnerable to increased N-loss through the soils becoming carbon-limited. This loss was reduced through biochar addition, highlighting the potential for optimising waste additions to both maximise several soil ecosystem services and promote carbon sequestration (Schofield et al., 2019). On possibly shorter timescales, there is evidence from pot trials that rebuilding (as opposed to building from scratch) degraded agricultural soils by adding both inorganic and organic waste amendments can increase micronutrient content of crops (e.g. Clarke et al., 2019, Gwandu et al., 2021).

Taking 5-20 years to build 'healthy' organic carbon rich soils and far less time to rebuild or nurture soils provides a powerful rationale for the need to urgently change policy to facilitate the rebuilding of agricultural soils with the right clean ‘waste’ minerals and organic matter.

7. A core framework to rebuild soils

Baas Becking and Beijrinck famously said about microbes, “*everything is everywhere, but the environment selects*” (De Wit and Bouvier, 2006). Engineers (including civil, mining and environmental) have a track record in the built environment and tackling big problems that involve soil and water. The premise of this paper is that engineers can help create the right environment by considering optimisation of the 4 broad constituents of soil as the raw materials for building soil as shown in Figure 1: soil organic matter, minerals, air and water.

Engineers and scientists can work with communities to consider what is missing (e.g. carbon or nutrient) from their particular soil’s natural cycle as well as considering particle size so that air and water can also be optimised. Establishing what is missing would involve laboratory analysis of the bioavailability of macro and micronutrients as well as an understanding of soil structure. Most cultivated arable systems are depleted in both macro and micro-nutrients (Roy et al., 2003, 2006) which come from both organic matter and minerals respectively. Sustained agricultural productivity now requires the constant input of the major nutrients of nitrogen, phosphorous and potassium, and the semi-regular input of the essential nutrients boron, calcium, copper, iron, magnesium, manganese, molybdenum and zinc (Constable et al., 2001, Roy et al., 2003). We must consider what the “right” minerals are to supply these micronutrients and maintain a healthy soil biome. Engineers can optimise coamendments of both minerals and organic matter to return to land to minimise rate-limiting effects of either macro or micronutrients and maximise the provision of ecosystem services.

7.1. The “right” mineral materials

The “right minerals” depends on what minerals are already present in the receiving soil and what ecosystem service a community wants. This might be healthy food or flood resilience.

The majority of soils are dominated by the mineral fraction (see Figure 1). This mineralogical composition and resulting texture of the soil is one of the most important static properties that affects soil function and often resilience to change. Primary and secondary minerals are normally accessed by the soil biome in one of two ways, either from the regolith (dictated by the underlying geology) at the bottom of the soil profile or from inputs at the top via the hydrosphere or atmosphere. Soil minerals are divided into different particle sizes: sand, silt and clay. The ‘clay’ phase represents a size fraction of <0.002mm but can include many different minerals including fine primary mineral particles as well as more (e.g. smectite) and less (e.g. kaolinite) chemically reactive secondary clay minerals and pedogenic Fe, Al and Mn oxides. The stabilisation of SOM by clays is well established (Franks et al., 2021; Mikutta et al., 2005; Singh et al., 2019). The mechanisms by which clay sized minerals stabilise SOC range from specific sorption, polymerisation and physical protection against microbial decomposition (Chorover and Amistadi, 2001; Lützow et al., 2006; Singh et al., 2019; Six et al., 1999). For Mn oxyhydroxides, although present at much lower concentrations than Fe and Al oxyhydroxides, their role is disproportionately important, and they have been found to be a key regulator of litter decomposition in soils (Keiluweit et al., 2015).

Soils in the tropics tend to be more intensively weathered than temperate soils (Minasny and Hartemink, 2012). When clay minerals are present in tropical soils, they are more likely to be less reactive 1:1 clay minerals such as kaolinite as well as iron and aluminium oxides. Temperate soils often have more reactive 2:1 clay minerals such as montmorillonite and illite and so have higher fertility, as these more ‘active’ clays have higher cation exchange capacities and higher surface areas. Sandy soils are common in the tropics and have very little surface area to support biological and pedological processes and so are not very fertile and most at risk against degradation and SOM loss (Yost and Hartemink, 2019). Using minerals to improve soil fertility is a well-established practice in many countries and often used to raise pH (Taylor et al., 2017), as well as providing a source of K (Manning and Theodoro, 2020). Addition of primary silicates can release alkalinity which also raises pH and enhances sequestration of CO_2 as inorganic carbon $CaCO_3$ has been practised in acidic soils in Brazil (Taylor et al., 2017). Since the microbiome facilitates SOM build up best at higher pHs (Malik et al., 2018) combining mineral amendments with organic matter to build up both inorganic and organic carbon stocks could be complimentary. However most mineral amendment work to date has focussed on the supply of macronutrients and has not addressed SOC build up or micronutrients.

The addition of safe mineral wastes to sandy soils creates a real opportunity for kickstarting SOC build up. Sandy soils cover large areas of the globe (approximately 900 million ha) especially in semi-arid regions such as Australia and sub-Saharan Africa (Yost and Hartemink, 2019), where they are increasingly being used for cultivation (Abalu and Hassan, 1998). Adding mineral wastes, such as foundry wastes, food processing wastes, mining wastes and water treatment sludges have all been shown to increase biomass production on sandy soils (Churchman et al., 2014, Clarke et al., 2019, Soda et al., 2006) which will increase the potential for carbon storage. Adding waste minerals has the advantage of providing fresh mineral surfaces free of SOC that could stabilise SOC in a less accessible form (Tipping and Rowe, 2019). Pedogenic clays often have a decreased capacity to adsorb and retain DOC due to existing organic coatings (Churchman et al., 2020). Addition of waste minerals not only provides fresh surfaces for SOC stabilisation but can also increase water holding capacity (see section on air and water) which moderates temperatures, improves biomass production and reduces wind erosion. All of these factors are likely to increase the organic C stocks of sandy soils.

Our opportunity for organic C sequestration lies in ensuring that the sequestration capacity of soils is fully utilised. When this sequestration capacity is inherently low, for example in sandy soils, the sequestration reservoir can be kickstarted by adding safe, soil-mimicking wastes or clays to create stabilising surfaces for organic matter (Tipping and Rowe, 2019). Engineering these soils for greater C storage could be the low hanging fruit for C stock increases, improved soil health and improved micronutrient rich food production.

7.2. The “right” organic materials

The “right” organic rich materials are provided in a natural soil cycle by diverse vegetation (Chen et al., 2018) via the biological carbon pump. There is a correlation between SOM build up and microbial activity (growth), but high microbial activity and SOM are not necessarily related to high microbial diversity (Zheng et al., 2019). Importantly in cultivated soils, there will always be take-off from the soil (whereas in natural systems, this take-off is returned locally) for both food, textiles and bioenergy crops, so communities must consider how they can return their organic-rich waste materials to the soil in order to ensure that they do not create a shortage of micronutrients that are not returned via photosynthesis. Returning of organic rich wastes by communities must be optimised to minimise any potential pollution from either methane and nitrous oxide production and/or nutrient leaching. Biological stabilisation techniques like composting are often needed and this can help reduce greenhouse gas emissions (egYoshida et al., 2015) on application to land.

However, organic rich wastes may well be lacking in micronutrients such as trace metals especially if they are missing in the soil where they were generated. This is where it will be beneficial to consider adding organic matter in conjunction with minerals which may contain the missing micronutrients. In addition to potentially promoting soil nutrition, local organic and inorganic wastes can be combined to rebuild contaminated land promoting either bioremediation e.g. waste minerals can be used to immobilise excess nutrients and remediate eutrophication (e.g. Turner et al., 2019) and potentially toxic element (PTE) contamination (Finlay et al., 2021). Biological processes including phyto- and mycorrhizal metabolic remediation (Gomes et al., 2020) can also be used for PTE immobilisation. Organic wastes can often contain persistent organic pollutants (POPs) such as endocrine disruptors and there is a growing body of work exploring the use of soil amendments both organic (Parlavecchia et al., 2020) and inorganic (eg Johnson et al., 2017) to immobilise them in the soil so that they do not transfer to humans through the food chain. Opportunities for using minerals to minimise risks from either POPs or PTEs will involve an understanding of the full biome, and an assessment of any associated pathogen and bioaccumulation risk (Stone et al., 2021).

7.3. Air and water

The sections above have outlined potential engineering interventions for building carbon in soils by providing the right macro and micronutrients for the biome. These interventions i.e. selective additions of chemically reactive metal oxides, clays, rock dusts, chars, composts and the planting of soil carbon-building plants will need to be chosen to suit different soil types under different land management regimens and climates. More generally, if we consider soils as self-organising dynamic systems such additions are likely to have profound effects on all the other physical, chemical and biological properties of soils which must be considered for soil rebuilding protocols. For instance, something not explicitly discussed so far is the impact these interventions may have on the availability, distribution and dynamics of two volumetrically major components of the soil system namely air and water. Such considerations will be more complicated because air and water distributions and dynamics will themselves reciprocally impact on organic carbon fate through direct control of microbial activities and mineral reactivities manifest through observable bulk or localised changes in soil biogeochemistry.

The principal controls on soil air and water distributions and are of course relatively well understood. Water input and output are externally dictated by the climate, weather and topography influencing long term average inputs and shorter-term variations e.g. flooding events. Of more relevance to rebuilding soils through soil engineering is the property of soil texture (i.e. mineral composition) whereby, for instance, sandy soils derived as larger granular particles from sandstones are typically well drained (sometimes overly so) and are aerobic (ultimately destabilising organic carbon), whilst, clay soils derived from finer clay particles often derived from weathered igneous rocks are typically poorly drained and prone to anoxia. Such clay soils may be subject to shrinkage and cracking during droughts. Although, it is usually assumed that soil texture (a property dictated by geology and geography) cannot be changed, envisaged additions of minerals during re-build may have important impacts on this property.

In addition to soil texture already discussed in the minerals section, the formation of biogeochemical micro-gradients (thermodynamically and mineral solubility controlled) within soil aggregates themselves gives rise to anoxic or physically occluded microsites in turn promoting soil organic carbon preservation. Reciprocally, it can be envisaged that added and stabilised organic matter will influence aggregate stability because aggregates (particularly macro-aggregates >0.25 mm) are physically held together not only by roots and fungal mycelia but also the soil organic matter itself which acts as a binding agent or as hydrophobic films stopping water infiltration. So critically, soil structure is subject to change either through deterioration by poor soil management, or to improvement through our envisaged introduction and stabilisation of organic matter except in highly weathered soils where Fe and Al oxides may provide the main agent that binds particles.

At a much finer scale than encompassed by the interaggregate pore cavities and channels discussed above, and of particular importance to agronomists, is a soils water holding capacity (WHC). This property refers to the water adsorbed onto, and dictated by the size of, the soils internal surface area. Critically, this surface area held water remains in the soil even after complete drainage and is more reliably available to plants. This surface area size is largely dictated by a soils clay content and to a lesser extent (in sandy soils) its organic matter and so it is easy to envisage the direct role that mineral additions e.g. clays and rock dusts and their weathering might play in changing WHC during soil rebuilding. However, building soil organic carbon is likely important as it is thought to contribute specifically to higher plant available WHC.

8. UN Sustainable Development Goals to consider in rebuilding soil health

The United Nations 17 Sustainable Development Goals are a good platform to consider all the issues that intersect with rebuilding soil health. There are many excellent reviews which cover issues that are important for soil security (e.g.McBratney et al., 2014) and soil health linking to climate change and food security (Lal, 2020). And there are many excellent existing frameworks and partnerships in place to help farmers consider these issues in the transition from conventional intensive to more regenerative farming practices such as the Toolkit for Agroecology Performance Evaluation, TAPE (Mottel et al., 2020). Dumont et al., (2021) considers socio-economic issues relevant to regenerative agriculture in more detail than we do here.

Importantly, communities will only be interested in rebuilding soils if it is economically viable and logistically feasible to do so. There are successful economic models to learn from such as the ‘zero budget’ farming that has been adopted by the State of Andhra Pradesh in India (Veluguri et al., 2021). The economic benefits associated with more regenerative farming are becoming clearer with a growing acknowledgement that this sort of farming is economically rewarding in terms of yields (eg van der Ploeg et al., 2019) but that the transition from conventional intensive agriculture to regenerative takes time.

One issue which requires much more research are the numerous site-specific cultural and economic factors that can aid women (SDG5) in adopting more regenerative farming practices (Zhang et al., 2017). In this section however, we only consider SDGs 4, 12 and 13.

8.1. Education (SDG4), circular economy (SDG12) and soil health

Breure et al., (2018) have stated that the health of the soil is a ‘prerequisite for closing the biological cycles in a circular economy’. It should be borne in mind, however, that at the moment, neither linear or circular economies prioritise the preservation and health of soil as an end goal. For instance, the focus is often on the soil’s role as a recipient of macronutrients (e.g. C N P K) through application of waste, or on the increasing need for bioenergy production although it is noted that this can create a battle between energy and soil, both vie-ing for the same carbon rich materials and often generating wastes with low C:N ratios (Johnson et al., 2018).

The ‘right environment’ for rebuilding soils is not just the right technical environment but the right socio-economic environment. Amundsen and Biardeau (2018) summarise governmental challenges in restoring soil health and highlights social mobilisation to affect change as a key challenge. We also highlight the need for policy-makers to urgently reclassify clean ‘waste’ minerals as by-products so that they can used in both urban and agricultural environments to rebuild soils.

In order to move from the vicious cycle to a virtuous circle, we must educate current and future generations about the fact that soil is living. We acknowledge that because soil health is complex we do not understand all of the interrelated mechanisms. The biosphere itself contains a myriad of complex interrelated biogeochemical cycles and we struggle to understand them with computational models. There is a lack of physical models to verify results, but it is possible to produce energetically open, materially closed systems (Milcu et al., 2012) which mimic the Earth’s biosphere. In terms of outreach and educational tools, at its simplest, this is soil in a jam-jar (see Soil in a jar - Figure 5) with different plants and minerals handled and assembled by children keen to get their hands dirty and to observe plant growth. This hands-on model represents soil's natural cycle where soil itself has a 'circular economy' with a balance of inputs and outputs (Rosemarin et al 2020).

At its most complicated the jam-jar set-up is a powerful scientific tool capable of measuring the interactions between minerals, organic matter, air, water and the living microbiome where mass balance calculations can be undertaken and missing micronutrient from human diets can be identified. We agree with Brevik et al., (2018) that connecting the public with soil via human health will be more helpful than focussing on carbon in helping us transition towards more sustainable farming practices.

An educational framework, of the soil as a living ecosystem with a natural cycle that requires care, not only provides a structural network in which to fit the chemistry, physics, atmospheric interactions, biology, governance and education, but also taps into the essence of what stirs and motivates governance and education: an "ethics of care". Studies show that we and our youth are disconnected and ignorant about soil (Johnson et al., 2020) with only 30% of children aware that 'soil is living'. This ignorance is likely related to the fact that firstly we do not teach this topic and this is partly because it is complicated. This complexity and heterogeneity of the data is also a problem at farm management level (de Bruyn and Abbey, 2003). If we cannot communicate why we should care for soil at the educational level, governance and farmer engagement is unlikely to succeed. The challenge in both education and policy lies in the simplifying and streamlining the science into an engaging framework that can be communicated at all levels, school, farmer and governance level.

The educational framework required to support a successful policy framework will involve as much learning as teaching at every level: garnering knowledge of the land from the farmers, indigenous knowledge of the lands, the local cultural/societal and governance constraints which will preclude implementation of the framework and knowledge of the wastes from government structures and industry, to connect it into one philosophy of caring for the land and restoring the soil's natural cycle as a whole. Without a focus on poverty and equitable land distribution, any educational attempts around soil health will be disconnected from the realities of caring for land (Juerges and Hansjürgens, 2018). Successful examples in Zimbabwe include the Farmer Learning Centres (FLCs) which connect science and society. Co-learning and co-innovation of regenerative farming practices by researchers, farmers, extension and agro-service providers (Mapfumo et al., 2013) in Zimbabwe have resulted in farmers adopting many regenerative practices which have resulted in increased yields and lower input costs (Mapangisana et al., 2020).

8.2. *Impact of the 'rebuild' framework and possible engineering interventions on climate forcing gasses (CO_2, CH_4 and N_2O) and their mitigation (SDG13)*

Like humans, living soil "breathes", breaking down its SOM 'food' producing and, in some cases, consuming gases such as CO_2, CH_4 and N_2O (see Figure 3). Since this process is biologically mediated it should be possible to factor such gas fluxes into a soil engineering 'rebuild' framework thus mitigating climate impacts. For CO_2 of course it is implicit that the engineered building of SOM will render soil an overall sink via autotrophic plants, photosynthetically producing energy and biomass. Some of the carbon fixed by plants will be shared as root exudates with the below ground microbiome in exchange for other nutrients. A proportion of this shared carbon will be respired to CO_2 by the microbiome's heterotrophic respiration (attributable to both fungi and bacteria as well as other soil fauna) but some known as necromass will be available to build up carbon if the right environment exists or is created (Zheng et al., 2019). It follows then that regenerative agricultural interventions like cover cropping (Kim et al., 2020) by enhancing carbon inputs to soils will improve the health and activity of the soil microbiome through root inputs. More biogeochemically orientated engineering interventions, for instance, adding crushed, fast-reacting silicate nutrient rich rocks to croplands (Beerling et al., 2018) could be considered as an additional CO_2-removal strategy through the formation of pedogenic carbonates by reaction of the respired CO_2 with rock sourced Mg and Ca.

From the discussion above it follows that higher microbial activity will correlate with higher carbon stocks and this is what is observed by Zhang et al., (2019). The stoichiometry of any added SOM and minerals which provides macro and micro-nutrients is therefore critical to microbial mineralization of SOM and also therefore to necromass build up (carbon sequestration) under aerobic conditions (Kirkby et al., 2014; Kirkby et al., 2016). However, with increasing drought cycles predicted, the Birch Effect - the renowned aerobic flux of CO_2 and N_2O (see below) released upon soil rewetting – on these carbon stocks is important to understand (Navarro-Garcia et al., 2012). Improving soil aggregation is known to decrease the microbial metabolic flux of C and N upon rewetting dried soils (Navarro-Garcia et al., 2012). Soil aggregation is controlled by interaction between SOM and minerals and so can be manipulated by engineers in their choice of the right mineral and organic amendments.

Leibeg's law of the minimum might suggest that engineers can create the right environment for a healthy microbiome by providing access to the right minerals and the right organic matter so that no one macro or micronutrient is rate limiting to the extent that ecosystem service provision in the soil is damaged. Often, the rate-limiting factors to microbial activity are not the macro-nutrients, but the micronutrients (which can be missing due to age or parent materials of soils) or the electron acceptors such as oxygen (Kirkby et al., 2013; Kirkby et al., 2014, Keiluweit et al., 2017). The balance between aerobic and anaerobic metabolism is therefore key to preserving nutrients and preventing the increase in mineralisation rates predicted with global warming. Although models often assume that aerobic respiration drives metabolism in uplands soils, recent work has shown that anaerobic microsites regulate soil carbon persistence, even in well-drained soils (Keiluweit et al., 2017). By shifting to less-efficient anaerobic respiration, otherwise (i.e. under aerobic conditions) bioavailable compounds are selectively protected, including reduced organic compounds such as lipids and waxes. Soil amendment technologies that include a range of particle sizes could facilitate the creation of soil microaggregates that contain anoxic zones allowing SOM build up whilst at the same time maintaining soil macroaggregates which are associated with macropores and oxidising conditions that favour plant growth and drainage.

N_2O is a considerably more potent GHG than CO_2 and emissions from conventional intensive agriculture come from both livestock manure and increased fertiliser application (Denman et al., 2017). It is of course well understood that more regenerative agricultural practices, such as those used by the Farmer Learning Centres in Zimbabwe, use biological N_2-fixation through co-planting crops with indigenous legumes and significantly reduce the need for chemical N additions (Nezomba et al., 2008). Optimising biological N fixation with indigenous legume planting gives maize yields of 2.5 t ha^{-1} on degraded sandy soils compared to 1 t ha^{-1} under continuous chemically fertilised (120 kg ha^{-1}) and natural fallow-based alternatives. In contrast to reducing chemical N additions which may not be feasible to maintain plant productivity, soil amendments to supress N_2O production have also been considered. For instance, it is estimated that liming could reduce total N_2O emissions by 15.7 % in acidic chemically fertilised soils representing approximately 37 % of French soil (Hénault et al., 2019). Alternatively, Shen et al., (2021) found that the application of coconut husks, employed as a soil conditioner in agriculture, provided a favourable habitat for fungivorous mites which rapidly consume fungal N_2O producers in soil, so they proposed that this amendment could be used to regulate N_2O production by fungi. Borchard et al. (2019) concluded that, while biochar applications reduced N_2O emissions by 38 %, that this was a short-lived effect with most reductions tending to be

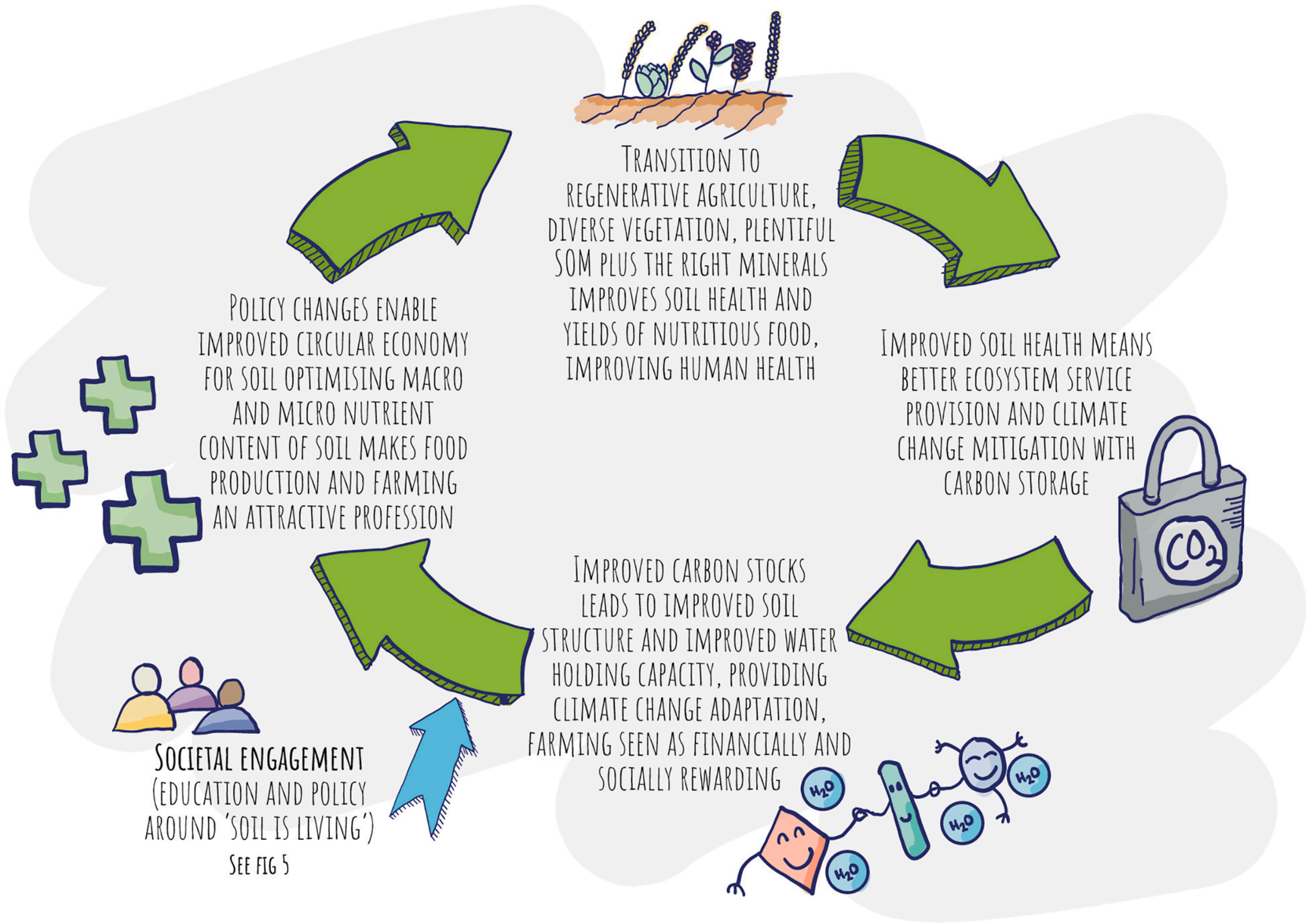

Figure 4. **The virtuous climate change – soil cycle** where communities engage with soil through a narrative of nurturing the soil because soil is living, thereby restoring soil's natural cycle allowing soil to rebuild. Integration of soil and water policies provide both climate change adaptation and mitigation at a local and global scale.

negligible after one year.

With respect to CH_4 this concerning and potent GHG is mainly produced in natural wetlands or rice paddies (Saunois et al 2020). In contrast emissions from drained cultivated land is, therefore, mainly from livestock and livestock wastes and there is little difference seen in CH_4 emissions between conventional arable agriculture or more regenerative farming (Biernat et al., 2020). However, soil rebuild interventions that affect soil texture, structure and hydrology are likely to have impacts on methane emissions as are amendments that provide key nutrients. For instance, aerobic (oxygen rich) sandy soils promoting methane oxidation certainly have fewer CH_4 emissions than clay dominated soils (Biernat et al., 2020). Such textural considerations may be important in constructed cover soils associated with landfills or natural gas production and transport infrastructures. With respect to hydrology, a water content that is too high ($> 20\%$) or too low ($< 5\%$) usually restricts the diffusion of methane in and out of soil (Shukla et al., 2013) and some soil systems shift regularly between a methane sink or source depending on seasonal water availability (Kolb and Horn, 2012). In terms of potential chemical rather than physical interventions, recent work (Wallenius et al., 2021) in marine studies has explored the role of alternative electron acceptors (nitrate, and manganese oxide) in promoting anaerobic oxidation of methane which may help reduce CH_4 emissions from anoxic soils. Alternatively, trace metals such as Cu (the key metal required for the enzyme particulate methane monooxygenase (pMMO) may provide stimulus for aerobic methane oxidizing bacteria (Guggenheim et al., 2019).

9. Conclusion

Decades of research in soil science has generated significant data but the complexity of the data has arguably prevented action: at an educational, community and policy level. We cannot afford to wait until we understand all the facets of soil and soil health before we act to reverse land degradation. We do understand that soil is living and that soil's natural cycle includes inputs of organic matter, minerals, air and water. And that the soil biome works with these inputs to optimise soil structure delivering soil ecosystem services in the process. We propose that engineers work with communities and scientists using a simplified technical framework to rebuild soils to optimise the ecosystem services they need such as food security (including enhancing micronutrient provision), and climate change mitigation and adaptation. This will involve site-specific characterisation of what is missing from their soil's natural cycle, as well as identification of where the right minerals and organic matter might be sourced to add to the soil. It will also include consideration of the particle size of any added minerals so that soil textures can be manipulated. We suggest that a narrative of 'soil is living' and exploring the links between soil health and human health will help with social mobilisation. We propose the use of 'soil in a jar' as an educational tool for children, farmers and policy-makers helping them establish both what is missing from the soil to help deliver ecosystem services and to connect them with soil on an emotional level. As well as the local benefits for communities - potentially improving micronutrient content of food and increasing yields from degraded soils

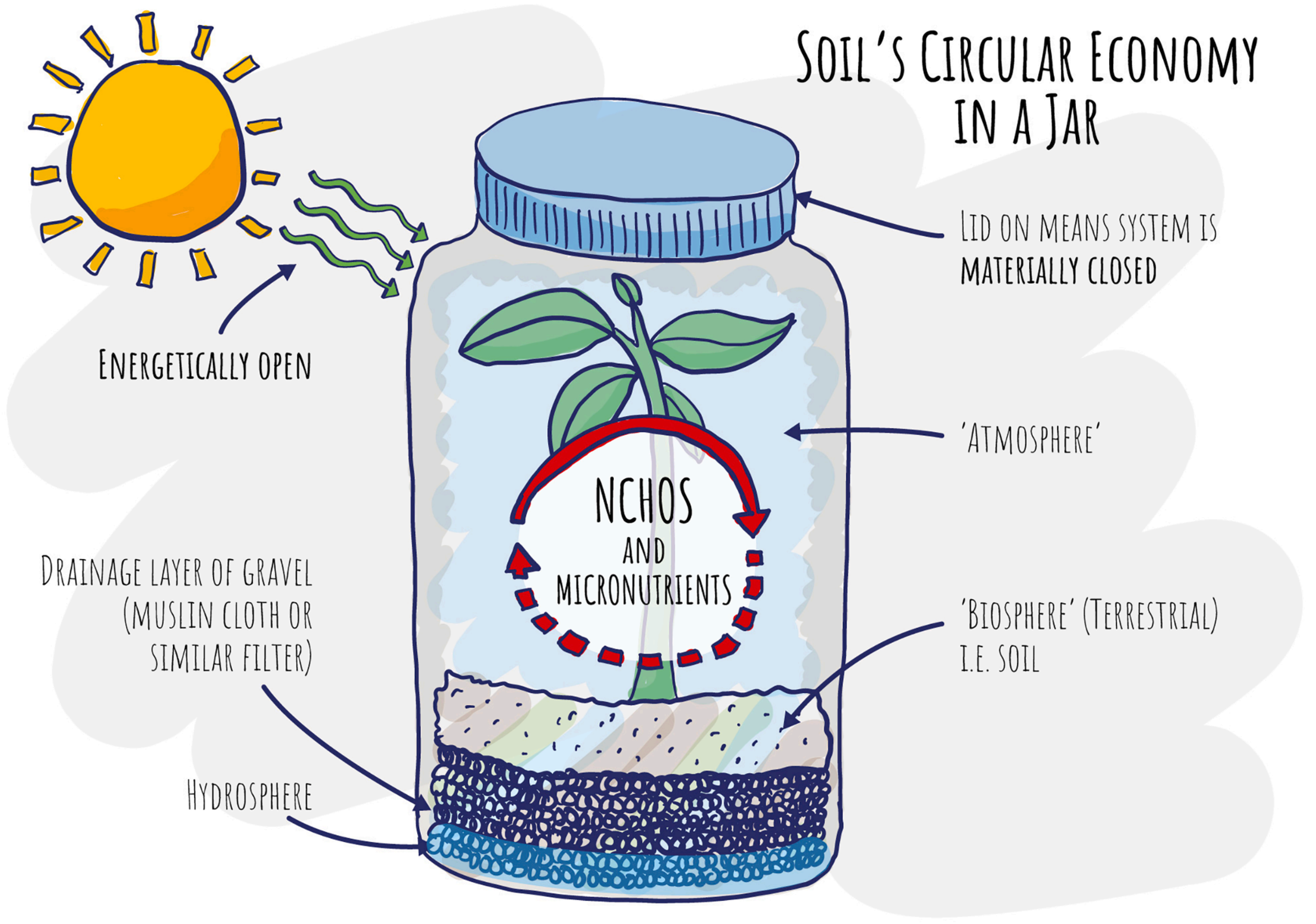

Figure 5. Soil in a jar - an energetically closed materially open system (Milcu et al., 2012) which can be as simple as a jam jar with one plant or a whole ecosystem representing a small biosphere. Here all wastes are reused as resources as would happen in soil's natural cycle and as is proposed in a 'circular economy' (Rosemarin et al 2020). Alongside the simplified system is the ability for every stakeholder (from children to farmers to policymakers of all ages) to get their hands dirty and learn about terrestrial biogeochemical cycle with endless scope for interdisciplinary learning. The rate of decomposition of a simple apple core can act as a soil health proxy. At the more technical end, there is technical knowledge to be built about what materials inputs help restore soil's natural cycle.

there are global benefits too. Once soil scientists have produced the much-needed robust tools to measure soil health, communities will be able to use the rebuild soils framework to help deliver SDG15 and SDG13. This rebuilding soils framework can facilitate nations in their move towards net zero by 2030 (Figure 4).

Declaration of Competing Interest

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

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