

**WHAT IS SOIL HEALTH?
THE FIRST STEP TOWARDS SUSTAINABILITY.**



LWS 548 Major Project

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EXECUTIVE SUMMARY

Conventional agriculture has supported the human population but has led to degradation of agroecosystems. The quality and the health of soil is rapidly deteriorating and becoming less fertile. Current agricultural practice poses threats to the environment causing degradation of water quality, land erosion, risking global food security and harming human health. These places of conventional agriculture are nearly abiotic, fewer and fewer organisms can survive in the soil due to excessive tillage and other inputs such as pesticides and herbicides. Policies, literature and Institutions have a lack of information of the role soil biodiversity plays in soil health and the health of the public. This literature review will discuss this knowledge gap and how soil health and its diversity is the first step towards a more sustainable practice. A holistic approach to sustainability would be one through which the alternative practices must protect the environment, be economically viable and socially fair. Economic viability was found to be the main barrier to adapting sustainable practices. Conventional agriculture is organized to a single crude principle, yield, where it may seem like this system is thriving on paper, but it is failing on nearly every other measure, such as the environment and human health that it is trying to sustain. It is critical that we start adapting strategies that regenerate the soil and are sustainable and viable for farmers to perform. Soil health and soil biodiversity is defined with their benefits to the agroecosystem and public health. The challenges and benefits of conventional, organic and regenerative agriculture are outlined, including their economic and social viability in their applications to sustainable agriculture.

INTRODUCTION

The natural world we observe and rely on is due to ecosystem processes which are complex physical and biological interactions and cycles. These processes result in ecosystem services that either directly enhance or sustain human life or maintain the quality of ecosystem goods. For example, soils and streams house microorganisms which seek their own sources of energy and life-preserving conditions, which remove contaminants from water, producing the service of “water purification” (Brown *et al.*, 2007). Ecosystem goods and services touch many aspects of human life, including the water we drink, the air we breathe, our food and our health. The ways in which ecosystem processes generate goods and services are mainly physical and biological scientists’ areas of interest, whereas the values and provision of the ecosystem goods and services are primarily economists’ area of interest (Brown *et al.*, 2007). Since ecosystem goods and services are of use to humans, they have a social and economic value. The human system (social and economic structure and function) sometimes feeds back to the ecosystem process as protection, but usually feeds back as negative externalities such as depletions and contaminations. The only way humans will change the negative feedback is if it affects us personally, and if the change is socially and economically viable. The economic value is very important within the agricultural sector because it determines the practice in which crops are produced.

We walk on soil, we plant on it, build on it, and drive on it. The soil beneath us is what gravity holds us to, but we often look at it as just dirt. Soil is so much more, it is an important part of the earth’s biosphere, functioning not only in the production of fiber and food but also the maintenance of local, regional and even global environmental quality (Doran *et al.*, 2000). It is also the basis of natural and agricultural plant communities. The thin layer of soil covering the earth’s surface can be the difference between extinction and survival. Thus, it is critical for farmers, gardeners, landowners, policy makers, and other stakeholders to understand what soil health is.

Soil is thought to hold the largest pool of undiscovered organisms, just a teaspoon of healthy soil can contain more organisms than the amount of people alive today (Lue, 2020). We are poor myopic humans, with neither the butterfly’s aptitude to see ultraviolet and polarized light, nor the ability of a hawk to see their prey at great distances. As humans we acknowledge that our vision is limited and there is much we cannot see. The communities within soil may be a mystery to scientists and the human eye, but they are known to one another. Their activities and interactions are extremely complex and vital for ecosystem goods and services that we depend on. Having a

high soil food web complexity can increase soil health and the resilience of an ecosystem, which improves the agricultural process and positively affects human well-being (Fitter *et al.*, 2005). This can also lead to increased vegetation health and nutrient acquisition, regulation of the hydrologic cycle, maintenance of the physical and chemical structure of soil, as well as the decomposition of organic matter (Bunning *et al.*, 2003).

Johnson (et al., 1997) defines soil quality as a measure of the condition of soil relative to the requirements of one or more biological species, and/or to any human purpose. However, the term soil health is preferred because it depicts soil as a dynamic living system mediated by a diversity of microorganisms. The concept of soil health is important for sustained environmental quality and productivity, which deals with the optimization and integration of the physical, biological and chemical processes of soil. Measuring the health of the soil can be done simply with a visual assessment and the smell and feel of the soil tilth, which is the prepared soil surface. For example, the feel of the soil can help in assessing the physical properties such as water infiltration. Soil biological characteristics can include the soil color, which may reflect the aerobic vs. anaerobic bacterial activity, and chemical properties can be measured by the smell; however, the soil productive capacity indicates human-induced degradation on nearly 40% of the world's agricultural land (Doran *et al.*, 2000). Among the causes of soil degradation are compaction, surface crusting, low organic matter, over grazing and land clearing (Moebius-Clune *et al.*, 2016). The issues of soil degradation have resulted in lower crop productivity, reduced soil health, lower abundance activity, and diversity of beneficial organisms and farm profitability (Moebius-Clune *et al.*, 2016). This rapid decrease of soil microorganisms in agriculture systems has had substantial negative effects on public health, the science of protecting and improving the health of people and their communities (Bayne *et al.*, n.d.).

The health of the soil has been intrinsically linked to human health and well-being, but there have been few attempts to understand the connection between public health and soil biodiversity. A reduced population of microorganisms in the soil has impacted human health both directly and indirectly. For example, a lowered soil biodiversity can reduce the yield of crops and their nutritional benefits harming food security and nutrition levels (Baudron *et al.*, 2018), which could cause malnutrition. Soil biodiversity also plays a major role of water purification in the hydrological cycle causing a decrease in water quality and an increase in non-point source pollution (NPS). A lower soil biodiversity population can also exuberate political conflict, and cause loss of income and livelihood. The loss of microorganisms in agriculture settings expands extensively to outside systems ultimately affecting the health of the public.

The “tyranny of small decisions” (Odum, 1982) in agricultural systems has led to monoculture practices to keep up with the increasing population. Historically, it has increased crop yields which has benefited humanity, but it has become one of the most pervasive problems in the Anthropocene. The past and current management of agriculture has significantly degraded and reduced the quality of soils throughout the world (Doran *et al.*, 2000). The projected population is expected to double over the next century, threatening accelerated degradation of soil (Doran *et al.*, 2000). We must incorporate sustainable agriculture systems to preserve and enhance soil quality for future generations.

Examples of sustainable practices that promote and maintain soil health are regenerative and organic agriculture. Regenerative agriculture includes a wide range of strategies such as, reduced and no tillage, and increased plant diversity and protective crop cover and crop rotation. Organic agriculture prohibits inputs of pesticides, synthetic fertilizers, and genetically modified organisms (GMOs). These alternative forms of agriculture have proven to improve soil health and increase the soil biodiversity population. However, a sustainable agricultural system must sustain the people and preserve the land.

Sustainability has three pillars, environmental protection, social equity, and economic viability. There is a considerable amount of literature looking at the environmental protection pillar to maintain soil health, but the definition of healthy soil and how it can be applied to economic viability is lacking. Therefore, alternative practices must be socially and economically viable, otherwise the current conventional agricultural practices will remain, and there is little to no economic incentive to change. We must change our perspective of soil and see it as a living system. It is only recently that the importance of understanding and managing the biological aspects of soil properties has become a focus in broader circles (Moebius-Clune *et al.*, 2016). Measuring and promoting soil biodiversity may be a step towards healthy soils and sustainable practices.

OBJECTIVES

The objective of this paper is to provide a review of soil health and its diversity on impacts of public health to provide recommendations towards sustainability within agricultural settings.

METHODS

A systematic analysis of existing literature that pertains to the objective was conducted.

LITERATURE REVIEW

Conventional Agriculture

Agriculture has been defined as the cultivation of the soil for growing crops and rearing of animals to provide food and other products to improve the human condition. Through the 1950s and the late 1960s a set of research technology transfer initiatives created the international Green Revolution, encouraged by the Rockefeller Foundation and other organizations (Kilby, 2019). The results were the adaptations of new technologies, aimed at cultivation and breeding. Cultivation technologies are targeted at providing good growing conditions such as irrigation, pesticides and synthetic fertilizers ("Green Revolution, 2021). Breeding technologies are targeted to improve crop varieties through science-based methods for example, high-yielding varieties (HYVs) of cereals, wheat, and rice. The Green Revolution was also associated with agrochemicals, controlled water-supply, chemical fertilizers, and mechanization. The purpose of the Revolution was to end world hunger by merging innovated technology into traditional agriculture, which is now known as conventional or industrial agriculture.

The developing world saw a phenomenal increase of food crop productivity growth over the past 50 years. During this time populations had more than doubled, but due to the Green Revolution the production of cereal crops tripled, with only a 30% increase in land area cultivated (Pingali, 2012). The widespread adoption of GMOs warrants a mention when discussing agricultural intensification, as the planted acreage of GMO crops increased 100-fold between 1996 and 2012 alone (Dornbush *et al.*, 2017). The worldwide increase of food production has helped to reduce poverty, lower food prices and gave a platform for economic development in the agriculture sector. The impacts of the Green Revolution on global food security are nearly impossible to assess because of the complexities of the food systems. Since the beginning of the Revolution the population has grown by approximately 5 billion. Without the Green Revolution, there would have been greater famine and malnutrition. Between 1950 and 1984, the world grain production increased by about 160% globally and in the developing nations, the average person consumes 25% more calories per day than before the Revolution ("Green Revolution", 2021). However, this

large-scale monoculture farming has brought its own challenges and problems, and it is seen as being unsustainable in the long run.

The productivity of conventional agriculture is maintained through a formidable reliance on costly tillage, fertilizers, pesticides, herbicides, machinery, defoliants, and crude oil. Farmers experience the highest suicide rate of any profession in the United States, a rate five-fold higher than the public; the driving depression rates are related to conventional production practices (LaCanne *et al.*, 2018). An indicator of the unsustainability of industrial agriculture is the ratio of energy outputs, the energy content of a food product (calories) – to the energy inputs (energy consumed in producing, processing, packaging, and distributing). While the agricultural output increased due to the Green Revolution, the energy input increased faster. Before the Revolution the energy ratio was close to 100, but today it is less than 1 in most cases, as energy inputs, mainly in the form of fossil fuels, have gradually increased, and if transport energy was included, the ratio would decrease further (Church, 2005).

Another perspective of industrial agriculture is to view it as the intentional application of external inputs in an attempt to close the yield gap between the potential yield (set by climatic limitations) and the realized yield obtained by producers. As seen in many intentional manipulations of ecosystem services, initial external investments provide large initial improvements in services, but returns on investment diminish through time as one seeks to continually enhance a given service to a higher and higher level (Dornbush *et al.*, 2017). This perspective shows a reality of decreasing yield gains, relative to economic input as the maximum potential yields are met. Since conventional agriculture has mainly focused on maximizing yield, a soil ecosystem service, which inherently undervalues and declines many other services that have been historically provided by agricultural soil ecosystems.

Our modern food production system has reduced the diversity of foods produced through the development and use of hybrid crops, synthetic fertilizers, GMOs and policies that decouple farmer decisions from market demands. This simplification contributes to the rising pollution, climate change, biodiversity loss and damaging land use changes that affect the sustainability, profitability, and resilience of farms (LaCanne *et al.*, 2018). The key macro-fertilizers that are traded and used are nitrogen and phosphorus which are of concern because when applied in excessive amounts lead to water pollution. This affects public health and aquatic ecosystems. The production of row crops and mechanical cultivations has resulted in the physical loss of soil, displacement through erosion, and large decreases in soil organic matter content with a

concomitant release of CO₂ into the atmosphere (Doran *et al.*, 2000). The practices of conventional agriculture cause soil degradation and soil habitat modification, which quickly changes the structure and physiochemical properties of soil, which in turn changes plant diversity and commonly reduces soil biodiversity.

While studying at the University of British Columbia in Dr. Hanspeter Schreier's class, I discovered that global projections suggest that food production must be increased by at least 50% between now and 2050. The main reasons for this are the rapid growth of the global population, the massive movement into cities, the rapid diet change as the economy in many countries improves, and that about 800 million people currently do not have access to sufficient food, and these problems are increasing. Maintaining crop productivity through soil health is key to meeting these challenges now, and in the future, because 95% of the food we eat comes from the soil. Climate change is indicated to have a significant impact on many of the globe's major cropping areas. Some of the expected impacts of the increasing climatic variability are higher temperatures, reduced total effective rainfall and changing rainfall patterns with increased rainfall intensity and erosivity. The increased climatic variability will play a major role in food prices in the future. The Food Commodity Index reflects the interrelationships between demand, energy costs, climatic variability, financial crisis and political conflicts, which has steadily increased over time. It is also expected that further increases will occur because of climate variability, decline in arable lands, trade restrictions, and soil degradation.

Since food demand will increase significantly over the next 30 years the continuous increase in the food price index will affect primarily the poor population of the world, which will likely increase conflicts. To meet these challenges and avoid negative impacts of climate change, soil health must be maintained. However, we are losing 30 soccer fields of soil every minute, mostly due to industrial farming, about a third of the world's soil has already been degraded. If current rates of soil degradation continue, all the world's topsoil could be gone within 60 years (Arsenault, 2014). Soil erosion can lead to up to 50% loss in crop yields, and in the European Union the economic cost of soil degradation is estimated to be in the order of tens of billions of euros annually (FAO, n.d.). Although, conventional agriculture has increased crop yields in order to eradicate global hunger, it is not sustainable in the long run.

Soil Health and Soil Biodiversity

Soil is not only the foundation of crops but is also an integral part of many key processes including, water supply, climate regulation and erosion regulation. It can take up to 200–1,000 years to produce just 2-3 cm (one inch) of soil. Soil health, within agricultural land use, refers to its capacity to sustain and support growth of crops and animals while also maintaining and improving the environment (Singh *et al.*, 2011). The term soil health and its definitions entail a holistic approach that views soil as alive as humans are.

Quantifiable soil quality parameters	Qualitative soil health characteristics
Particle size distribution	Texture, feel
Water stake aggregation, mean weight diameter	Tilth, cloddiness
Pore size distribution and total porosity	Internal drainage
Water retention capacity	Droughtiness, inundation
Erodibility	Prone to erosion
Infiltration capacity/rate	Time to ponding
pH	Taste, smell
Cation/anion exchange capacity	Buffering
Electrical conductivity	Salinity
Nutrient concentration and availability	Fertility
Soil organic carbon concentration	Color, smell
Microbial biomass carbon	Biodiversity
Time to recover/restore following disturbance	Resilience

Table 1: Parameters to measure and express soil health. Retrieved from: Singh *et al.*, 2011

The integrated holistic approach is based on the concept that the whole is bigger than the sum of its components. The components include soil properties, processes, and synergistic interactions among them. The properties that are strong determinants and maintain soil health are soil tilth (structure and texture), good internal drainage, optimal nutrient and water retention capacities. An essential part of maintaining soil process and properties, and hence soil health, is an optimal level of soil organic matter (SOM). To be in good health, soil must also be relatively free from pests and pathogens including, weeds and nematodes, and have adequate nutrient reserves and suitable elemental concentrations and balance (Singh *et al.*, 2011). Figure 1 illustrates that the

concept of soil health is integrated with the chemical, biological and physical components. The quality of the soil is assessed by measuring and identifying quantifiable parameters, and soil health parameters are measured qualitatively by using a composite soil health index and several biological indicators (Table 1). The parameters are specific to three distinct but interrelated components: physical, biological and chemical (Singh *et al.*, 2011). The sum of the components provides many functions and ecosystem services such as net primary production (NPP), improving air quality, water purification, enhancing the environment, and moderating climate at local, regional, and global scales. Soil organisms are an essential driver of the components and properties that maintain soil health and ecosystem goods and services.

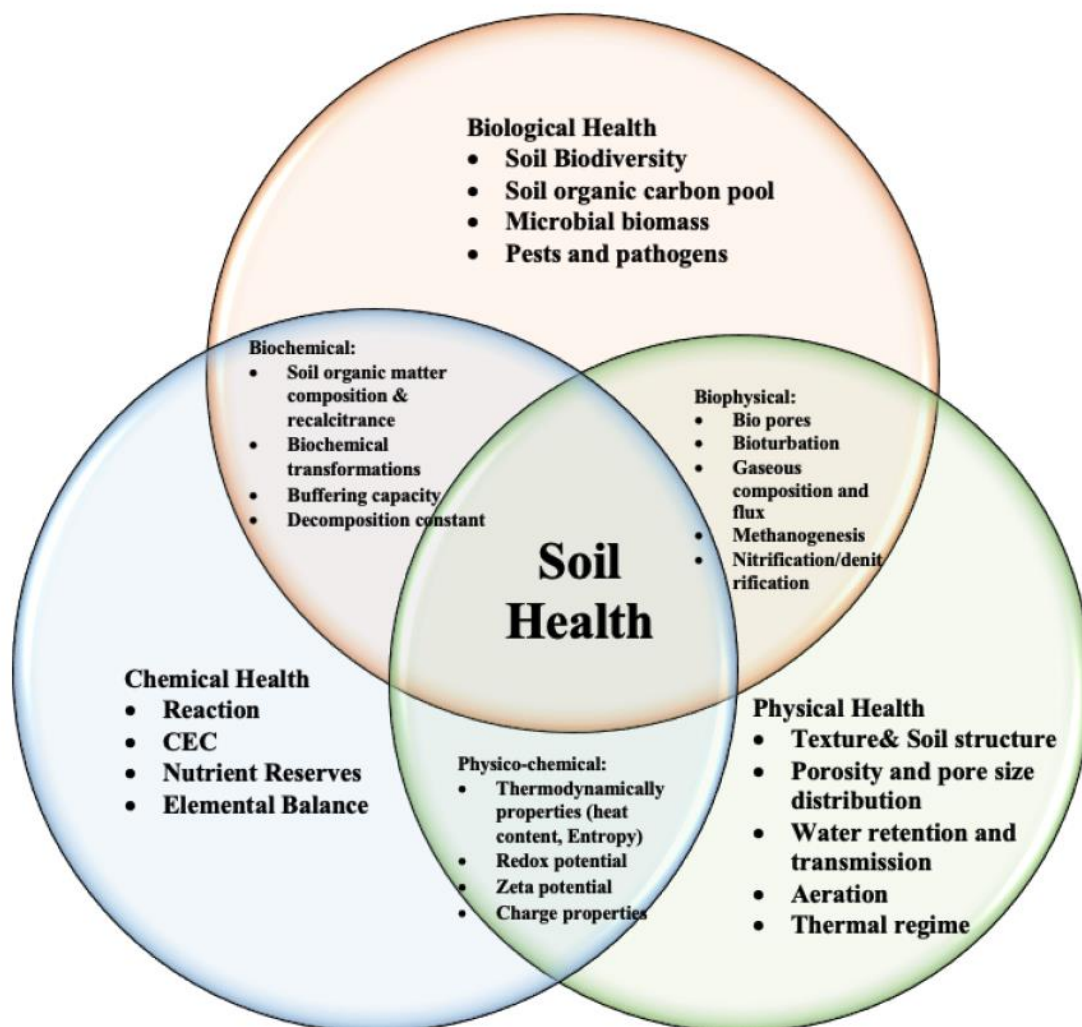


Figure 1: Soil health deals with integrating the physical, biological and chemical components of the soil. Retrieved from: Singh *et al.*, 2011

The soil ecosystem consists of both abiotic and biotic components, and these components interact with each other for the proper function of the ecosystem (Neemisha *et al.*, 2020). The abiotic part includes nutrients, mineral particles, water, gases, and nonliving organic matter. The biotic component includes soil organisms. They are critical within the structure of the soil, nutrient cycling, decomposition of organic matter, sequestration of soil carbon, greenhouse gas (GHG) emissions and the restoration of soil. Soil organisms are also an integral part of ecosystem functions such as water storage, detoxification of toxicants and suppression of noxious and pathogenic organisms (Doran *et al.*, 2000). They are defined as any organism that inhabits the soil during part or all of its life, which include, soil megafauna, mesofauna, microfauna, and microflora. Each have their own role to play in the physical, biological and chemical component of soil health, as illustrated in Figure 2 and described in Table 2.

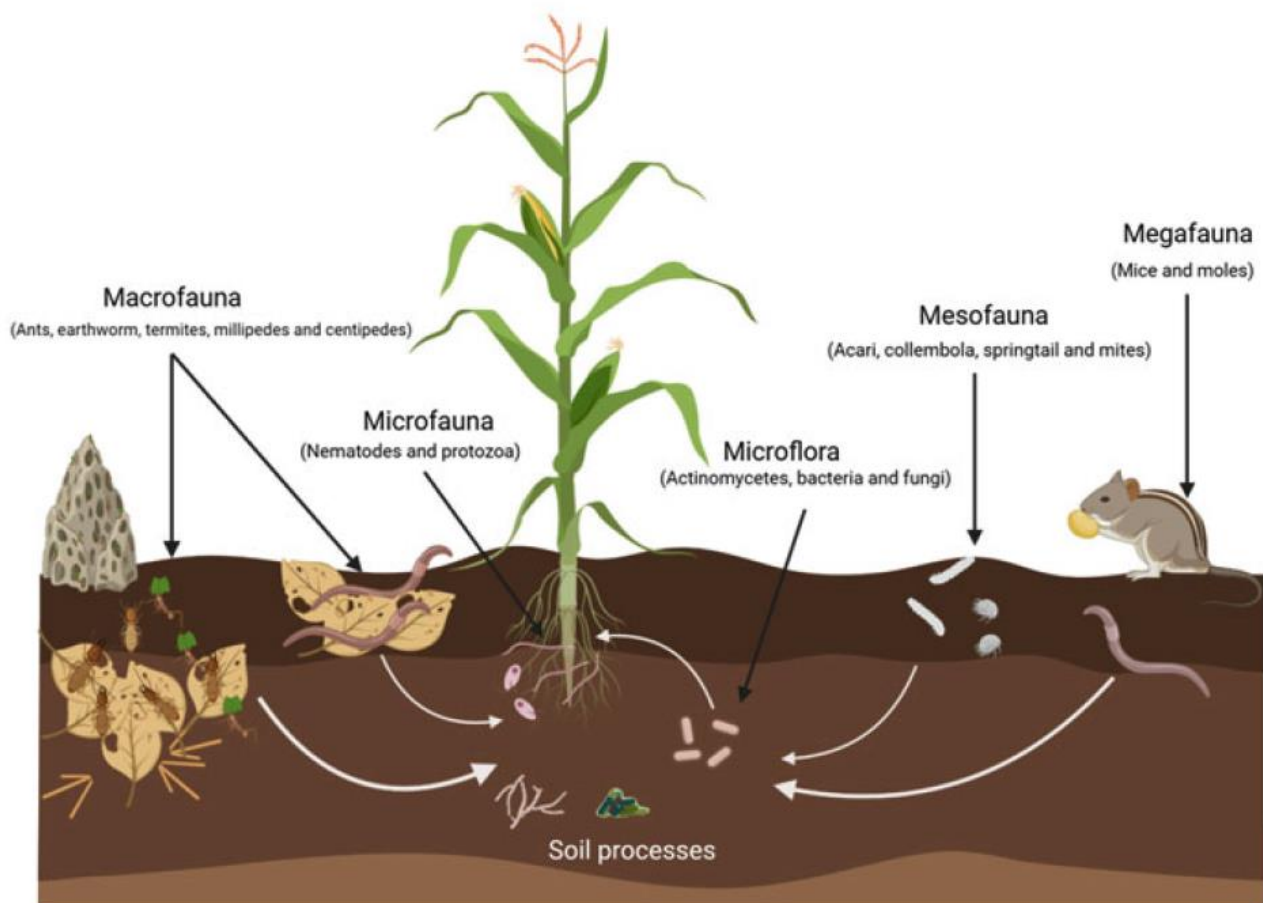


Figure 2: A representation of soil organisms and their function. Retrieved from: Neemisha *et al.*,

Classification of Dominant Soil Organisms		
Classes	Organism	Function in Soil
Megafauna	Soil Dwelling Animals: - Mice - Moles - Groundhogs	<ul style="list-style-type: none"> • Soil turnover, distribution and loosens soil structure • Improves aeration and drainage • Distributes soil microorganisms
Macrofauna (500µm– 50mm)	Earthworms	<ul style="list-style-type: none"> • Improves the structure of the soil, aeration and water infiltration • Casts are rich in organic matter, microbes and nutrients which improves nutrient cycling • Modify food quality through its passage in the gut • Mineralization of organic matter and realisation of nutrients • Disseminates bacteria and spores in soil
	Ants	<ul style="list-style-type: none"> • Important in mixing soil from lower depth with surface soil, and redistribute nutrients around the ecosystem • Turn and aerate the soil • Consume a variety of foods
	Termites	<ul style="list-style-type: none"> • Formation of biogenic structure • Eat soil organisms, organic matter and maintain equilibrium
Mesofauna (80µm – 2mm)	Acari Collembola	<ul style="list-style-type: none"> • Feeds on bacteria, fungi, mineral soil particles, organic matter, protozoa and nematodes • Important biological control agents for crops and feeds on pathogenic fungi • Important food sources for predacious mites and beetles
Microfauna (5 – 120µm)	Protozoa	<ul style="list-style-type: none"> • Nutrient turnover in the rhizosphere • Production of plant growth promoting substances • Phagotrophic with bacteria, fungi, algae and other fine particulate organic matter
	Nematodes	<ul style="list-style-type: none"> • Nutrient turnover, and decomposes soil organic matter
	Fungi	<ul style="list-style-type: none"> • Decomposition of organic matter • Promotion of soil aggregation, nutrient cycling and biocontrol of plant pathogens • Degradation of wastes and harmful chemicals
Microflora (1-100µm)	Bacteria	<ul style="list-style-type: none"> • Nutrient cycling and organic matter decomposition • Production of industrially important secondary metabolites and degrades wastes and harmful chemicals
	Actinomycetes	<ul style="list-style-type: none"> • Decomposition of soil organic matter • Release of nutrients • Very important in curing compost • Inhibit the growth of several plant pathogens in the rhizosphere • Biological buffering of soils
	Viruses, Viroids Mycoplasmas, Prions	<ul style="list-style-type: none"> • Influence ecology of soil biological communities • Turnover of nutrients and gases

Table 2: Classification of soil organisms. Information Retrieved from: Neemisha *et al.*, 2020

Soil microorganisms or soil microflora are very important in developing a healthy soil structure. Microbes secrete substances such as polysaccharides that help in cementing soil aggregates which prevents crumbling on exposure to water. Fungi have a large surface area which adds stability to soil structure and are considered the most successful inhabitants of soil. Soil microorganisms are classified into three types depending on their functions in the soil habitat: ecosystem engineers, chemical engineers, and biological regulators (Neemisha *et al.*, 2020). Ecosystem engineers create and modify habitats by constructing resistant aggregates and pores, which act as a hotspot for reproduction of other organisms. Ecosystem engineers decompose organic matter and provide nutrients. Biological regulators are predators of plants, invertebrates and microorganisms, and regulate their dynamics in space and time (Neemisha *et al.*, 2020). Microorganisms are very important as they drive the most significant biogeochemical cycles in soil and are primary decomposers of organic matter.

The interactions between each trophic level are significant in regulating the soil processes. Figure 3 shows a simplified version of the complex interactions in the soil food web. For example, ecosystem engineers act as a regulator of resources for other organisms and the interactions between microorganisms and nematodes regulate the microbial population. However, the agriculture paradigm has shown to have harmful effects on the soil biota.

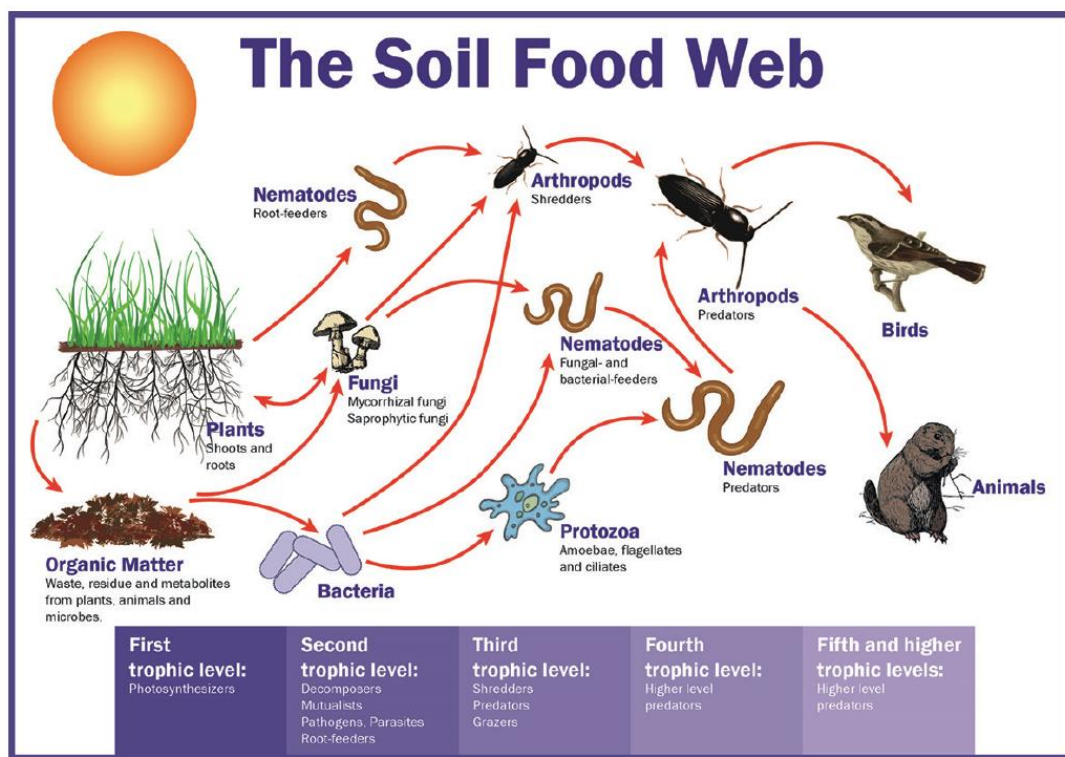


Figure 3: An example of a topological soil food web. Retrieved from: Rhodes, 2017

Conventional agriculture depends on irrigation, use of heavy machinery, tillage and increased application of pesticides and chemical fertilizers. These practices cause habitat modification that immediately change soil structure and physicochemical properties, which, together with changes in plant biodiversity affect and commonly reduce soil biodiversity (Geisen *et al.*, 2019). For example, microbial communities are shifting into bacteria dominated, and soil tillage and other agricultural practices are killing earthworms and disrupting mycorrhizal fungi. Heavy metal pollution and runoff have also been shown to kill microbial taxa and change the community composition of soil. Pesticide and herbicide use such as neonicotinoids and glyphosate can remain in the soil for many years and can impact non-target organisms in the soil. Studies have shown that common non-target effects are evident for neonicotinoids, as they are assumed to be causative agents of above-ground insect declines, but also can kill soil invertebrates including insects and earthworms (Geisen *et al.*, 2019).

A study by Postma-Blaauw (*et al.*, 2010) investigated the effects of agricultural intensification on major taxonomic soil biota groups, on trophic group structure of nematodes, predatory mites and earthworms, and on life strategy groups of nematodes and predatory mites. The researchers found that conventional agriculture resulted in reduced abundances of soil biota and changed functional group compositions. Larger-sized biota (earthworms, enchytraeids, microarthropods and nematodes) appeared to be more negatively affected than smaller-sized soil biota (protozoans, bacteria, fungi) in the short term by conversions such as soil disturbance. Also, the functional group diversity and composition were more negatively affected in larger-sized soil biota than smaller-sized soil biota. However, smaller-sized biota were more negatively affected by long-term consequences of conversion, probably due to the loss of soil organic matter but benefited in the short-term due to the increased nutrient availability. In general, conventional agricultural practices have disrupted and simplified the food soil web, because the microbial community are interrelated and when disrupted it can have a rapid effect on other species in the community (Figure 4). Since the 1990's food web modeling has helped to explore the consequences of changes in soil community composition and structure of soil processes, mainly with carbon and nitrogen mineralization, indicating that the contribution of different trophic groups of organisms to nitrogen mineralization varied strongly among farming ecosystems (Mujtar *et al.*, 2019). These studies have reported a reduction in species richness and interconnectedness in agricultural land compared to grassland and native forest soils. Lupatini (*et al.*, 2014) conducted a study in Brazil (Figure 4), which shows a native tropical forest soil that was first transformed into grasslands and

then into annual cropping of soybeans. The results were that the interactions of food soil web could be more important determinants of soil health and its processes.

Soil biota is also a useful indicator of soil health. Measurements of soil organisms meet many (though not all) of the five criteria for useful indicators of sustainable land management (Doran *et al.*, 2000). Soil organisms are good indicators in the criteria of sensitivity to changes in management to reflect the influence of management and climate on long-term changes, but not too sensitive to be affected by short-term weather patterns. The below-ground organisms also meet the criteria of being well correlated with beneficial soil functions, because their abundance and diversity have been shown to provide many soil functions such as, storing and releasing of water, decomposition of plant and animal residues, and promoting plant health. Soil organisms also meet the third criteria, useful for elucidating ecosystem processes. They can provide information on why the soil will or will not function, which helps land managers make decisions to optimize productivity and health of plants. The fourth criteria describes that an indicator must be comprehensible and useful to land managers. Programs in both the US and Ecuador have successfully included that the measurement of abundance and diversity of earthworms, mites, nematodes and bacteria could provide a wealth of information on soil function and processes but can require too much specialized training for land managers (Doran *et al.*, 2000). This leads to the last criteria, easy and inexpensive to measure. Sadly, measuring soil organisms requires a substantial amount of knowledge, can be costly, and extremely time consuming. However, it can be possible to develop measurements for land managers, but research is needed to develop sampling methods. Soil organisms are good indicators of soil health because they are sensitive to land-use and climate changes, are correlated with soil functions and processes and are great teaching tools due to elucidating ecosystem processes. On the other hand, developments need to be made for soil organism measurements that are meaningful, useful, and accessible for land managers.

Wall (*et al.*, 2015) discussed the fact that global conventions that are central to soils and global land use, such as the UN Convention to Combat Desertification, the UN Framework Convention on Climate Change, and the UN Convention on Biological Diversity often neglect soil biodiversity and our dependence on soil for human health, with the exception of the CBD14 through the Food and Agricultural Organization (FAO). However, developments are being made because the importance of soil biodiversity is becoming more recognized as an essential part of many ecosystem goods and services, especially in agricultural settings. The UN FAO has brought together global institutions and other parties through the Global Soil Partnership to organize

agreements and international challenges connected to soil sustainability. Wall (*et al.*, 2015) stated that progress towards the Sustainable Development Goals can be attained by incorporating knowledge of soil biodiversity into a broader spectrum of benefits that improve human health. Most importantly, the recent establishment of Global soil biodiversity Initiative is an independent scientific effort to provide information on soil biodiversity to policy makers. This initiative is preparing to publish the first Global Soil Biodiversity Atlas in collaboration with European Union Joint Research Centre (Wall *et al.*, 2015), and is also working to have soil biodiversity considered in current international initiatives like the Ecosystem Services and Future Earth and the Intergovernmental Platform on Biodiversity.

Soil biota plays an important role in agroecosystem functioning and that the disturbances in soil biota negatively affects the agroecosystem. The reductions in microbiota abundances can affect nutrient mineralization (Postma-Blaauw *et al.*, 2010), and the reduced abundances of earthworms and predatory mites which can result in reduced bioturbation, disease control and water infiltration, thereby enhancing the risk of increased water erosion. In general, the loss and shifts of soil biodiversity can lead to a reduction of soil multifunctionality which pose threats to the sustainability of ecosystems and human health.

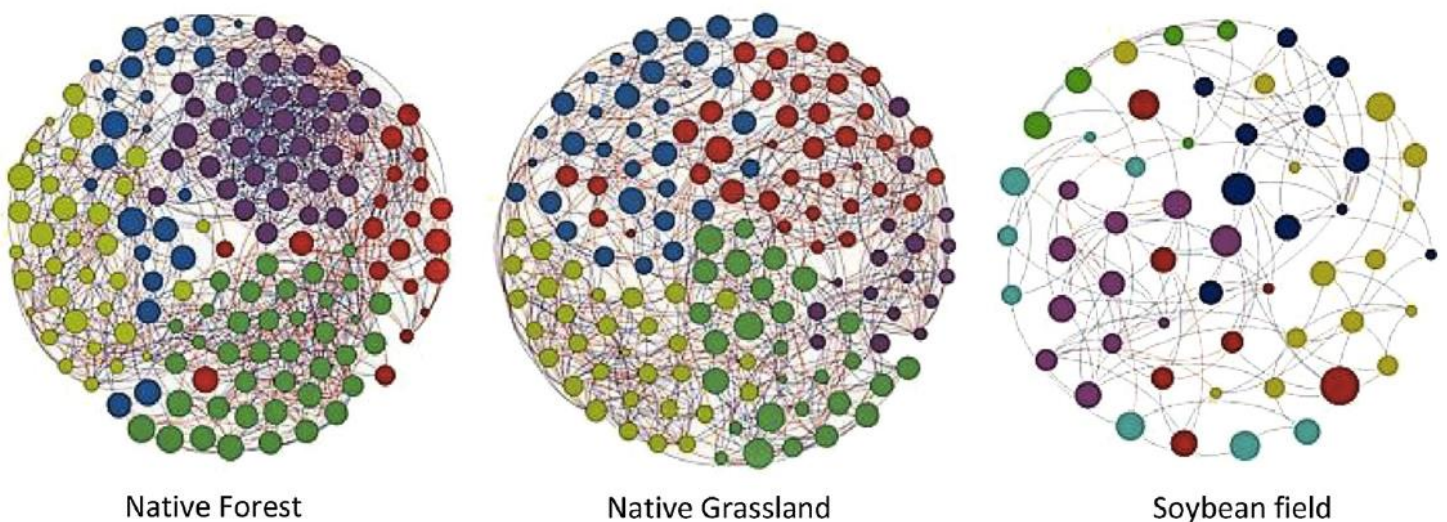


Figure 4: Bacterial network analysis in soil samples taken along a gradient of land use types. Different colors indicate different groups of taxa containing key metabolic potential capacities. Each dot corresponds to a bacterial genus and its sizes is proportional to the value of closeness centrality. Retrieved from: Mujtar *et al.*, 2019

Public Health and Soil Organisms

Soil health and public health are strongly related, and it has been increasingly recognized that soil biodiversity provides benefits to human health. Soil biodiversity can suppress disease-causing soil organisms, provide clean air, water, and nutritious food (Wall *et al.*, 2015). However intensive agriculture has declined the population of soil biodiversity resulting in reduced and impaired benefits far beyond the original state of disturbance. Poor land management and climate change have decreased soil biodiversity which leads to a loss of ecosystem goods and services that negatively impacts human health (Figure 5), as well as the economic value of the goods and services. This section will discuss how soil biodiversity in agroecosystems specifically affects public health by assessing plant and human diseases, water quality and quantity, as well as food security and nutritional content.

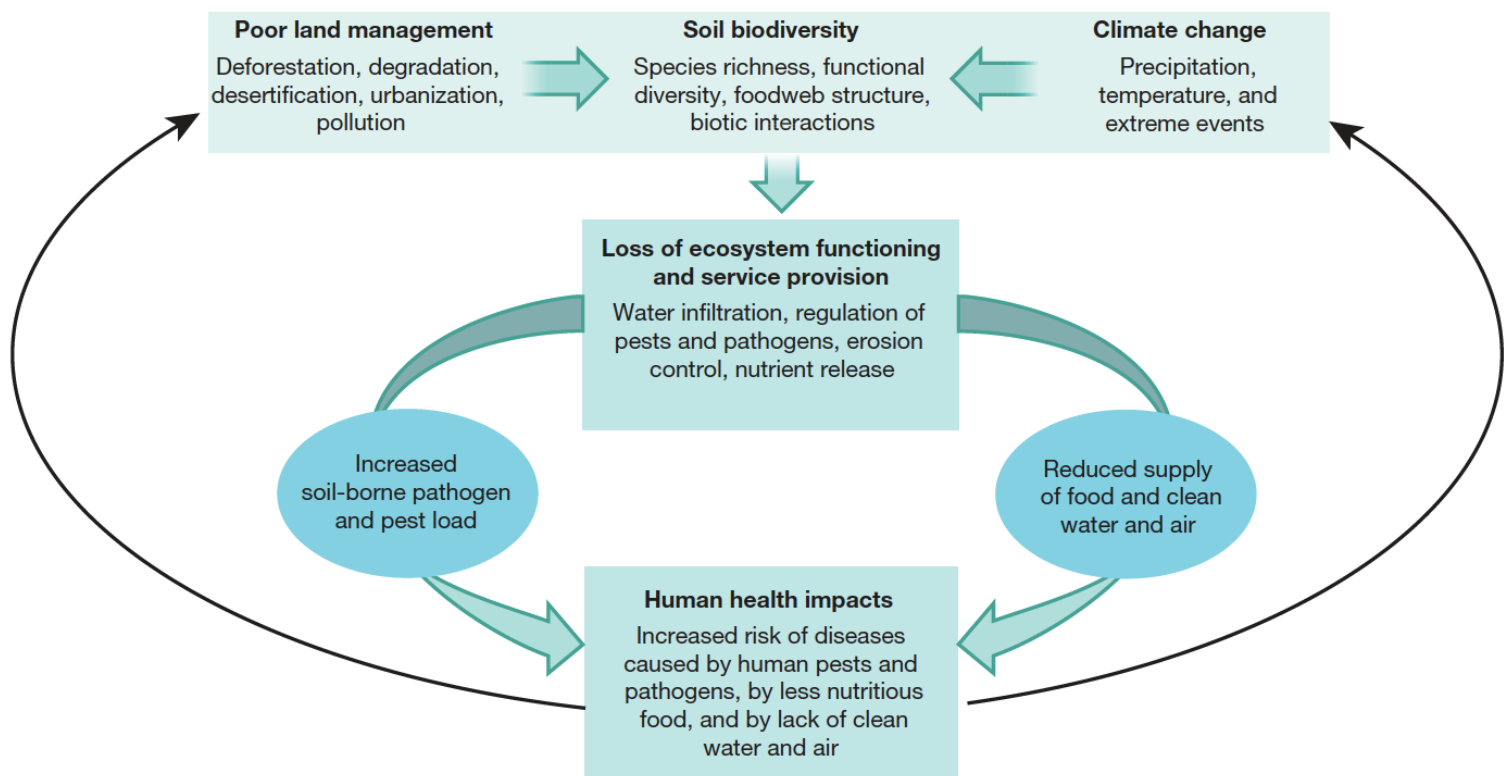


Figure 5: Diagram illustrating the link between soil biodiversity and human health.

Retrieved from: Wall *et al.*, 2015

DISEASES

The dynamic inhabitants of soil and their interactions provide many benefits such as disease control for humans, plants, and animals. Soil-borne parasites and pathogens that affect humans are a minority of organisms living in the soil, and there are many positive effects of soil biodiversity on human health through their roles (direct and indirect) in controlling soil-borne pathogens and pests. Some soil-borne pathogens can be opportunistic or obligate species. Most of these organisms can survive in soil for weeks to years, including spores and eggs (Wall *et al.*, 2015). Pathogens that can cause human infections can either be inhabitants of soils (euedaphic) or transmitted via soils.

The research of Wall (*et al.*, 2015) describes a nematode, *Strongyloides*, which is a soil transmitted helminth and a parasite of humans and animals that has a unique life cycle that alternates between free-living in soil and parasitic. In the soil food web, the free-living form feeds on bacteria. However, the parasitic form when in contact with a suitable host penetrates the skin and migrates to the intestine where they reproduce causing *Strongyloides stercoralis* infections. In Cambodia, about 45% of the people tested were infected, and a higher risk of infection was associated with lower soil organic carbon (SOC) content, and land-use conversion from forest to cropland (Wall *et al.*, 2015). These results suggest that increasing the soil organic carbon levels in agriculture could be effective in reducing the prevalence of disease-causing helminths. Conventional agriculture, particularly the tillage practices in the Midwest United States has shown losses of 40-60% of SOC relative to historic levels (Dornbush *et al.*, 2017), which could have resounding impacts on public health but due to access to sanitation and health care the risk is lower. Research by Fierer (*et al.*, 2003) documented increases in gram-positive bacteria and decreases in gram-negative bacteria, fungi and protozoa with depth, and concluded that they were driven by differences in SOC availability and quality across the soil profile. The vertical patterns of microbial enzyme activity showed similar declining patterns with depth, which suggests a link between microbial community structure, SOC availability and potential SOC turnover rates (Dornbush *et al.*, 2017). Soil biodiversity loss may also cause an increase in allergies. Studies have shown that our immune system needs to be exposed to possible pathogens residing in soil in order to develop tolerance. Another concern of altered soils and associated losses in above and belowground biodiversity is that we are losing a possible source of antibiotics and medicines as well as the biological controls to prevent human, animal, and plant diseases.

In conventional agricultural systems, soil borne pathogens can reduce plant above and belowground biomass, disrupt the metabolic flow of nutrients within plants, or even kill the plant entirely, all leading to the production of less nutritious food (Wall *et al.*, 2015), ultimately affecting food security and malnutrition, whereas an increased soil food web can benefit the crop. For example, Wang (*et al.*, 2020) showed that AMF increases plant tolerance to disease and reduces damages by various plant pathogens; and Hu (*et al.*, 2016) showed by increasing the diversity of *Pseudomonas* probiotic consortia enhances the microbial community survival of the rhizosphere, which leads to an increased suppression of a bacterial pathogen in tomatoes. These studies and others show the importance of soil biodiversity interactions on suppressing pathogens and increasing crop productivity.

WATER QUALITY

Soil biodiversity affects the availability of potable water by regulating the hydrological cycle. The organisms enhance the structure of the soil and enhance the filtration of water through the soil profile (Wall *et al.*, 2015). This improves water-use efficiency by crops, limits the amount of runoff, filters out pathogens and contaminants, and the organisms can degrade harmful pollutants. Low soil biodiversity can increase the risk of nutrients being lost via leaching and water runoff, which can lead to ground and surface water contamination (Janion-Scheepers, 2020). For example, an enteric bacterium that is found in water and soils, *Enterobacter cloacae*, can effectively bioremediate selenium-contaminated agricultural drainage water. Selenium is an essential micronutrient for humans but can accumulate in irrigated river basins and evaporative ponds.

Conventional agriculture contributes large amounts of pollution into water systems via runoff and is defined as a NPS. The main pollutants being nitrogen (N) and phosphorous (P) from excessive fertilizer use, which can cause severe environmental problems such as reduced biodiversity, eutrophication, surface and groundwater pollution, and contributes to global warming. The major water contaminant in North America and Europe is nitrate nitrogen. Human alterations of the nitrogen cycle have almost doubled the rate of nitrogen from land to the atmosphere and to rivers, estuaries, and coastal oceans (Doran *et al.*, 2000). The high yields of conventional agriculture are often achieved with the aid of excessive fertilizer use, but only about 50% of N inputs are used by crops and a large fraction that remains unused are lost through leaching and gas emissions (Bender *et al.*, 2015). Not only does an excess amount of nitrate nitrogen harm the environment but also human health. It cannot be tasted, smelled, or seen and consuming too much nitrate can

be harmful, especially for babies. The major concern is for people who live near farms and drink from well water, which is quite common in agricultural areas. Consuming too much nitrate can affect how blood carries oxygen and can cause methemoglobinemia, also known as blue baby syndrome ("Nitrate in Drinking Water", n.d.). It can cause the skin to turn a blue color and can result in death. People with pre-existing conditions are also at a higher risk of developing nitrate-induced methemoglobinemia. The biggest losses of N and P have been shown to be in areas under intensive agriculture, where soil biodiversity is often reduced (Bender *et al.*, 2015). In the soil the most nutrient transformations are performed by soil organisms through their activities; they drive nutrient cycling and play a role in determining if nutrients are stored in the soil or if they are available to plants. A study performed by Bender (*et al.*, 2015) investigated the influence of soil biota ranging between 11 μ and 2mm, arbuscular mycorrhizal fungi (AMF) and soil micro and mesofauna on nutrient leaching of N and P in outdoor lysimeters over the course of 2 years. The results showed that soil life significantly reduced relative P leaching losses by -25% and relative N losses by -36%. This indicates that high nutrient losses in conventional agriculture may generate from the disruption of soil food webs and affect several ecosystem functions including water systems that we rely on.

A Fundamental way to reduce the agricultural yield gap is the delivery of reliable, adequate, and relatively stable soil moisture content (Dornbush *et al.*, 2017). Humans consume about 50% of surface freshwater with agriculture accounting for approximately 33%, globally. One of the main ways to improve water efficiency in agriculture is to maintain good soil conditions that enhance the water holding capacity. Soil organisms influence the soil texture and carbon content which plays a role in how much water can be stored in soils. Organic carbon and clay minerals have a lot of negative charges that hold water with adhesive and cohesive forces. Increasing the carbon content in soil increases water holding capacity, improves nutrient retention, and is a part of carbon sequestration. Improving the abundance and diversity of soil organisms can increase soil carbon which is an effective way to improve the moisture retention and resiliency of soils to the effects of increased climatic variability.

FOOD SECURITY AND NUTRITION

The yield of crops has increased due to the Green Revolution, but production has to be increased by at least 50% between now and 2050. The Green Revolution has maxed out in improving yields, decreased the nutritious content in crops and already 0.8 billion people do not have enough food.

Crop quality and yield is directly linked to soil health and soil organisms. For example, termites can increase yields in warmer and drier climates, and earthworms have shown to increase crop productivity in humid and cooler climates. Soil symbionts have a very important role in food production, they are essential for nutrient supply and can contribute to biofortification of plants for important micronutrients such as zinc (Wall *et al.*, 2015). The most notable and the most studied is AMF. These fungi interact with almost all edible crops; they improve soil health and help with acquisition of otherwise inaccessible nutrients from the soil, transfer them to their host plant, and thereby improve plant nutrition and the nutritional content of our food.

Human health is indirectly influenced by agricultural management practices that affect the nutritional value of crops, and the quantity of food produced (Wall *et al.*, 2015), through soil organic matter and soil structure formation, nutrient retention, and cycling; these effects may also result in greater plant resistance to the increasing climatic variability (Mujtar *et al.*, 2019). Human nutrition depends on the balance and availability of nutrients in the soil and the ability of plants to take in those nutrients. The lack of soil biodiversity interactions that improve plant uptake can lead to specific nutrient deficiencies in the food produced. In developed countries, the focus on increasing crop yield has led to a decreased nutritional content of food (Mujtar *et al.*, 2019), which in some cases may have led to malnutrition.

The indirect influence of soil biodiversity impacting the quantity and quality of food produced can be represented by the study performed by Bender (*et al.*, 2015), which also investigated the influence of soil biota on nutrient-use efficiency and plant performance. Since there was a significant reduction in P and N leaching due to enriched soil life, this demonstrates that nutrient-use efficiency was increased in the enriched soil-life treatment. The researchers compared their results from enriched soil life lysimeters to reduced soil life lysimeters. Bender (*et al.*, 2015) found an increase of total N in plant biomass by 17.8% in the enriched soil life treatment. Total P in plant biomass of the enriched soil life lysimeters increased by 72.3%. These results demonstrate that soil biodiversity contributes to agriculture by supporting plant nutrient uptake and plant yield.

Soil biodiversity plays a crucial role in providing a stable supply of food with a higher nutritional content. However, the intensification of agricultural practices in the last century has ignored this role of soil biodiversity (Wall *et al.*, 2015). The use of tillage, fertilizer and agrochemicals have been linked to soil biodiversity loss, these practices shouldn't be abolished but practiced sustainably. Crops produced today can support most of the global population, but sustainable use of soils is necessary for long-term human health.

Sustainability

Before talking about the possible solutions, sustainability must be discussed, because it is a dangerous word especially in the agricultural sector. Usually, the term sustainability isn't discussed in the abstract. Most people that attempt to live sustainably do so by changing their diet or changing the products they buy. To see the concept in its entirety, the three pillars of sustainability are used. The pillars represent environmental protection, economic viability, and social equality. Economic stability can be defined as the capacity of a system to continuously provide goods and services whose values exceed the cost of production (Robertson, 2015). The calculation is straightforward, but it becomes tricky when adding the values of inputs and products that are taken for granted like soil biodiversity or externalized such as nitrate pollution. This is a large problem for agriculture and has made an intensive area of economic inquiry. Social sustainability embraces the capacity of a system to continue to meet the expectations of society for social justice and security, including intergenerational equity (Robertson, 2015). A principal requirement of a just society is food security and the promise of accessible and stable food supply, as well as rural vitality and community health.

The pillars are intertwined and are the roots of sustainability, which can only be achieved if the three pillars are balanced. However, balanced does not mean equal, and in many cases one piece of the puzzle might be more important than the others (Krosowsky, 2021). There are many ways to perceive the pillars as to which is the most important. For example, by protecting the environment we are protecting our future and future generations. Neither social nor economic systems can exist if there is no environment, which is very important in the agriculture sector as previously discussed. In this view the environment is the most important and must be balanced first, otherwise society would fail. However, economic, and social systems may determine what happens to the environment. An agricultural producer may not be able to change their practices to better the environment if the change is not economically viable. On the other hand, if a change is made that costs the producer more money, they will most likely sell their crops for more money to achieve an economically viable situation, but this increase in price may not be socially equitable and would exclude low-income and minority communities from access to healthy food.

The economically viable pillar is the dominant pillar in the work to create a sustainable agricultural system. If it is not viable, either the change away from conventional agriculture won't happen, which will be devastating for the environment and ultimately our future, or the produce would be too expensive, limiting accesses to minority and low-income communities.

Possible Solutions

Research shows that soil biodiversity can be restored and maintained if agricultural land is managed sustainably. The management of soil biodiversity can potentially increase agricultural productivity by increasing yield stability and the nutrition quality and safety of crops, making efficient use of limited resources, reducing production costs and economic risks for farmers; all of which contribute decisively to food security (Mujtar *et al.*, 2019). Soil biodiversity management also has the potential to increase the provision of ecosystem goods and services at local, regional and global levels. Promoting the ecological complexity and robustness of soil biodiversity through improved management practices represents an underutilized resource with the ability to improve human health (Wall *et al.*, 2015).

ORGANIC AGRICULTURE

The most widely known form of sustainable farming is organic agriculture, but only 1% of agricultural land is under organic agriculture. It could be defined as the opposite of conventional farming. Organic agriculture prohibits nearly all synthetic inputs and all the inputs that are used must be approved. In general, organic farming is often reported to have positive effects on soil biota, for example the biomass of protozoa and nematodes is usually found to be increased, compared to conventionally managed soils (Bender *et al.*, 2015). Organic farming has been considered one of the most effective tools to attain sustainable agroecosystems. Yakav (*et al.*, 2018) describes that organic agriculture assists to maintain a sustainable ecosystem, boost in biological cycles, usage of renewable resources, balance between animal husbandry and crop production, increased soil health, and the biodiversity of the production system and its surroundings, including the protection of plant wildlife habitats.

While organic farming may benefit the environment, the other two pillars of sustainability remain left out of balance. Due to low economic viability the cost of food is 20% to 60% more expensive (The Canadian Press, 2018) in comparison to inorganic food. There is also a large yield gap, resulting from the limited availability of nutrients. Knapp (2019) investigated annual yield variations in a meta-analysis and found that organic farming produces lower yields than conventional farming—on average 16% lower across all crops. However, increases of soil organisms could lead to increased plant production over longer time spans (Geisen *et al.*, 2019).

Therefore, organic agriculture may not be currently sustainable due to the higher cost of crops, lower yields, and low economic viability.

REGENERATIVE AGRICULTURE

Nothing is sustainable over the long term if it is not also regenerative. Many agricultural practices labelled as 'sustainable' in fact represent relatively small improvements with farming methods, and merely slow down the rate of deterioration on a landscape (Rhodes, 2017). The term, regenerative agriculture was coined by organic farming researchers at the Rodale Institute in the 1980s. However, it should be noted that "black and indigenous farmers have been practicing this form of agriculture without any title or performative acknowledgement for generations", which Fassler (2021) quoted from Angela Dawson. This practice of farming avoids chemical pesticides, and uses methods such as, crop rotation, composting, low to no-till farming, agroforestry and agroecology (see Table 3 for examples); all of which results in an increase of arable topsoil. It consists of holistic farming practices which aims to improve soil health and reverse climate change by expanding biodiversity, increasing organic matter, improving the water cycle, and transferring carbon from the atmosphere to the soil ("Regenerative Agriculture", 2020). At its core, its intention is to improve or restore the health of soil, which enhances water quality, vegetation, and the productivity of land. By taking a holistic approach, regenerative agriculture practitioners often integrate social considerations related to supporting sustainable livelihoods for farmers. Some of the facets considered include fair working conditions on the farm, the resilience and revitalization of the rural communities and landscapes in which regenerative farming functions, as well as the wider local and regional food systems to which farms are intimately connected (Electris *et al.*, 2019).

Regenerative Agriculture Practices	
Strategy	Soil Health and Soil Biodiversity Effects
Low to no Tillage	<ul style="list-style-type: none"> - Conserves soil organic matter - Maintains soil C & N levels - Limits disturbance that would otherwise destroy the soil structure that protects soil organisms that create natural soil fertility - Enhances soil fertility
Cover Cropping	<ul style="list-style-type: none"> - Provides a natural coat of armor which protects the soil from wind and water erosion - Provides food and habitat for macro- and micro organisms - Regulates soil temperature for soil protection and for a healthy soil surface biological process
Agroforestry	<ul style="list-style-type: none"> - Promotes diversity of both plant and animal species in a agroecosystem which plays a role in soil health and soil biodiversity
Maintain living roots	<ul style="list-style-type: none"> - Living roots feed soil biology by providing its basic food source, carbon. Soil organisms, in turn fuels the nutrient cycle that feeds plants

Table 3: Examples of regenerative / sustainable agricultural practices. Information Retrieved from: White, 2020 and Sherwood *et al.*, 2000

Regenerative agriculture can enrich soil life, soil health, ecosystem goods and services and ultimately public health. Management practices such as stubble retention and reduced tillage were shown to increase the abundance of nematodes, protozoa, mites and collembolan (Bender *et al.*, 2015). Strip tilling combined with cover-cropping showed to increase mites, nematodes and collembolan. Reduced tillage and fertilizer inputs have also shown to promote the population of AMF and its ability to support plant uptake of phosphorous. Phosphorous is usually applied in excess, because a large fraction of the phosphorous quickly reacts with the soil environment rendering it unavailable to plants, but in the presence of soil biota, soil phosphorous resources normally unavailable to plants can efficiently be mobilized (Bender *et al.*, 2015). Phosphorous fertilization could then be reduced, saving limited resources. AMF can also reduce the use of pesticides, enhance crop resistance to pathogens, and reduce the biomass of weeds by 20% to 66% (Wang *et al.*, 2019). Less frequent tillage can promote diversity of larger soil organisms, thereby leading to improvements in soil structure and nutrient cycling potential, whereas conventional farming with increasing tillage reduces soil heterogeneity at small spatial scales, with apparent reductions to the overall complexity of the soil community (Dornbush *et al.*, 2017). This is seen in Figure 6, a soil health research site that shows a side-by-side comparison of soils reacting to various management practices. Regenerative agriculture is not only sustainable in the means of not harming the soil but enhances the quality with practices that regenerates soil.

LaCanne (*et al.*, 2018) evaluated the effects of regenerative and conventional corn production and found regenerative farming systems provided greater ecosystem services and profitability for farmers than in conventional farming. The researchers showed that pests were 10-fold less abundant in insecticide-free regenerative farms compared to treated fields, meaning that farmers who design pest-resilient systems outperform farmers that react to pest with chemicals. They also found that regenerative fields had 29% lower grain production, but 78% higher profits over conventional corn production. Low to no-tillage, and avoidance of chemical inputs have been shown to reduce crop yields, but this varies greatly depending on local conditions, the type of crop and management practices. The increase of profitability was not related to grain yields, but it was positively correlated with the level of particulate organic matter. Meaning that promoting organic matter and soil biodiversity required less costly inputs such as fertilizers and insecticides. Profitability may have also been increased due to a diversified income and that farmers can increase the price of their products through marketing. These results show that ecologically based farming could be used simultaneously to produce food and conserving natural resources, which are two factors that are usually against each other in the conventional food production system (LaCanne *et al.*, 2019).

Regenerating the agroecosystem not only provides benefits for environmental measures but also socio-economic measures. Research has shown that regenerative agriculture increases soil biodiversity which in turn increases the water quality and reduces the amount of water used for irrigation, produces nutrient dense food, decreases the potential of diseases in animals, plants, and humans. This system of farming also provides a future for food security by regenerating the soil and making the ecosystem more resilient to climatic variability, sequestering large amounts of carbon in the atmosphere which helps to curb challenges with climate change. Electris (*et al.*, 2019) explains that the agriculture sector in the United States accounts for a total of 9% of greenhouse gas (GHGs) emissions, but practices that focus on soil health have the potential to increase the total global climate mitigation by approximately 30% through emissions reduction and sequestration. This is more than sectors such as electricity, transport, and the built urban environment can sequester. However, the researchers suggest that implementation of regenerative practices would require more than \$700 billion in estimated net capital expenditure over the next 30 years, but these practices could mitigate approximately 17 GtCO₂e, while generating a nearly \$10 trillion net financial return. Even though regenerative agriculture is beneficial for the environment and can be considered economically viable, farmers are still reluctant to take the added cost and complexity inherent to these methods. It shifts the nature of

the work away from yield and toward the management of a functional ecosystem (Fassler, 2021). There probably isn't a single farmer who wouldn't want to change to regenerative and sustainable agriculture, but the system that they are in indicates that they must grow a yield of X on a X number of acres to make their payments. However, Electris (*et al.*, 2019) demonstrates that regenerative agriculture over the long term is economically viable for investors, which can give farmers an opportunity to take a financial risk. The movements away from conventional towards regenerative agriculture must be slow, in order to be viable in the short term and socially equitable in terms of food pricing.

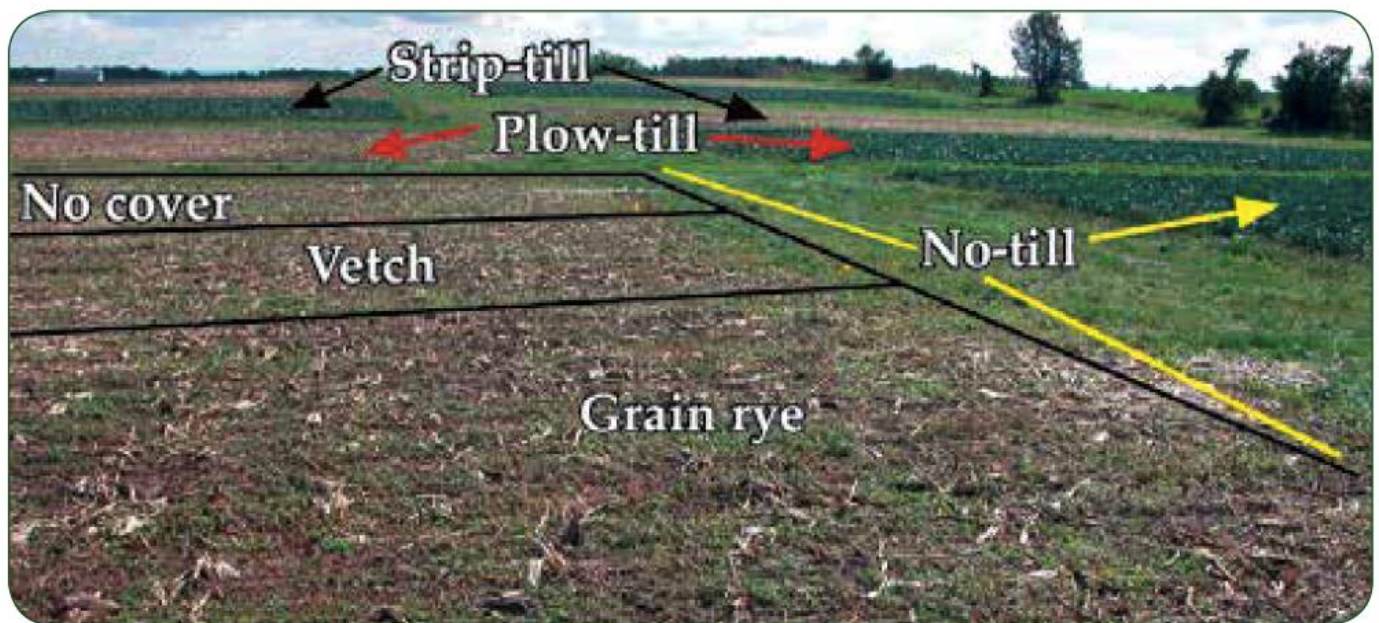


Figure 6: Represents three tillage systems, three cover crops and two rotation treatments.
Retrieved from: Moebius-Clune *et al.*, 2016

SYNTHESIS

So which agricultural systems are sustainable? Noted earlier, the pillars of sustainability are as follows, economically viable, environmentally safe, and socially acceptable. As discussed in the previous sections there is no one practice that is perfect. There are many permutations of sustainable practices as there are combinations of cropping systems, local environments, and social contexts (Robertson, 2015). However, sustainable systems share at least two attributes: they are resource conservative, and they rely more on internal ecosystem services than on external inputs (Robertson, 2015). As seen in Figure 7, there is an increase of holistic thinking and less inputs and energy required as you move farther from conventional agriculture towards sustainable and regenerative systems. Promoting soil biodiversity is the fundamental building block and the basis for sustainable crop productivity of resource conservation. Soil biodiversity also provides the reliance on processes internal to the farm and can be managed to optimize the delivery of their ecosystem services.

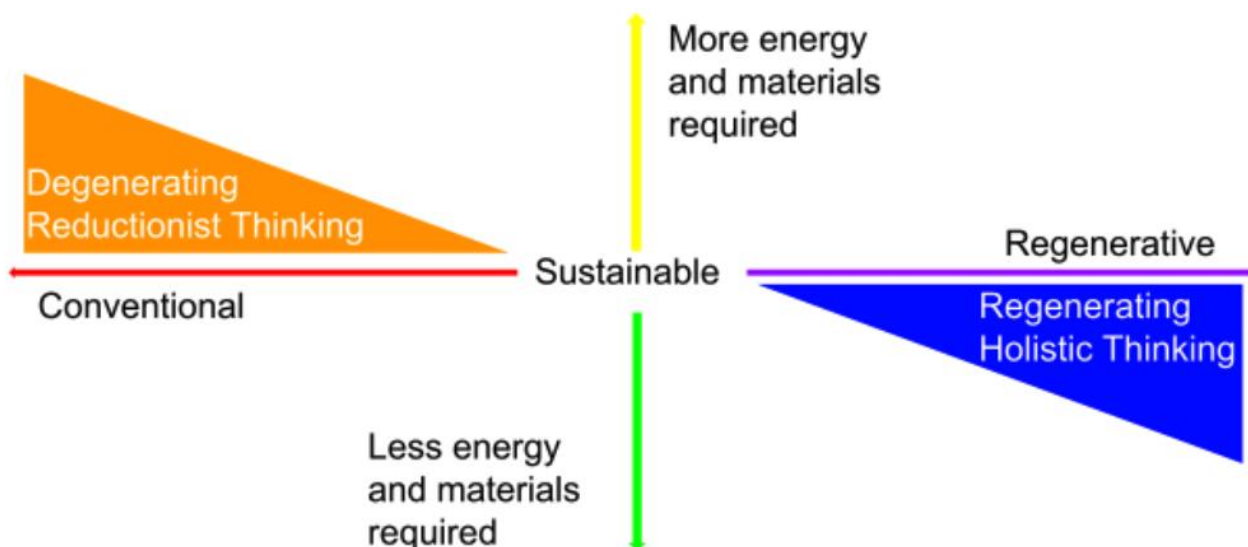


Figure 7: Model representing agricultural systems and energy inputs. Information Retrieved from: Electris *et al.*, 2019

The soil sustains—the basic principle of humus farming. We are only beginning to understand the importance of soil biodiversity in agriculture, which has historically and largely been ignored. From the research discussed earlier we know that by promoting soil biodiversity, farmers can avoid erosion and build new soil organic matter. Soil organic matter typically declines 40% to 60% upon conversion of natural lands to cropland or pasture (Robertson, 2015). The organic matter is critical, it provides a habitat and energy for soil organisms which provides a soil structure that is favorable for roots and water retention, as well as a chemical composition that delivers nutrients to plants. However, promoting soil biodiversity to ultimately optimize production in a sustainable fashion, full knowledge of trade-offs is needed. For example, a no-till system can help increase the soil biodiversity which in turn helps to build soil organic matter and thus is a resource-conserving sustainable cropping practice. On the other hand, tilling is used to control weeds early in the season, so in the absence of tilling, weeds must be controlled with herbicides. With sufficient knowledge such trade-offs can be minimized, and practices with multiple co-benefits can be encouraged (Robertson, 2015). Having a holistic view of cropping practices provides a complete picture of indirect synergies, direct benefits and trade-offs.

In order to understand the importance of these trade-offs, we first need to conceptualize ecosystem services in the context of the social and economic system. Ecosystem goods and services can be separated into four classes: provision, such as food, fiber, and potable water; regulation, such as disease and flood control; supporting, such as soil formation and nutrient cycling; and cultural, such as aesthetic and recreational amenities (Robertson, 2015). How ecosystem services affect people influences how ecosystems are managed. Brown (*et al.*, 2017) presents a model (Figure 8) which shows ecosystem services as outcomes of ecosystem interactions, such as biotic activities and interactions that inhabit agricultural soil ecosystems. These interactions result in outcomes that benefit people (ecosystem services). The behavior of people from the resulting service affects how the service is managed. Management can lead to protection such as organic or regenerative agriculture or depletions such as, water pollution. The inputs of management in agriculture can be intentional for example, crop selection, tillage, chemical inputs, and cover crops, but can lead to unintentional effects on the cropping systems such as diseases and pests. How people perceive ecosystem services and how the services consequently modify behaviors and policies result in changes to ecosystem inputs and management, which affects the delivery of ecosystem services, and the cycle continues.

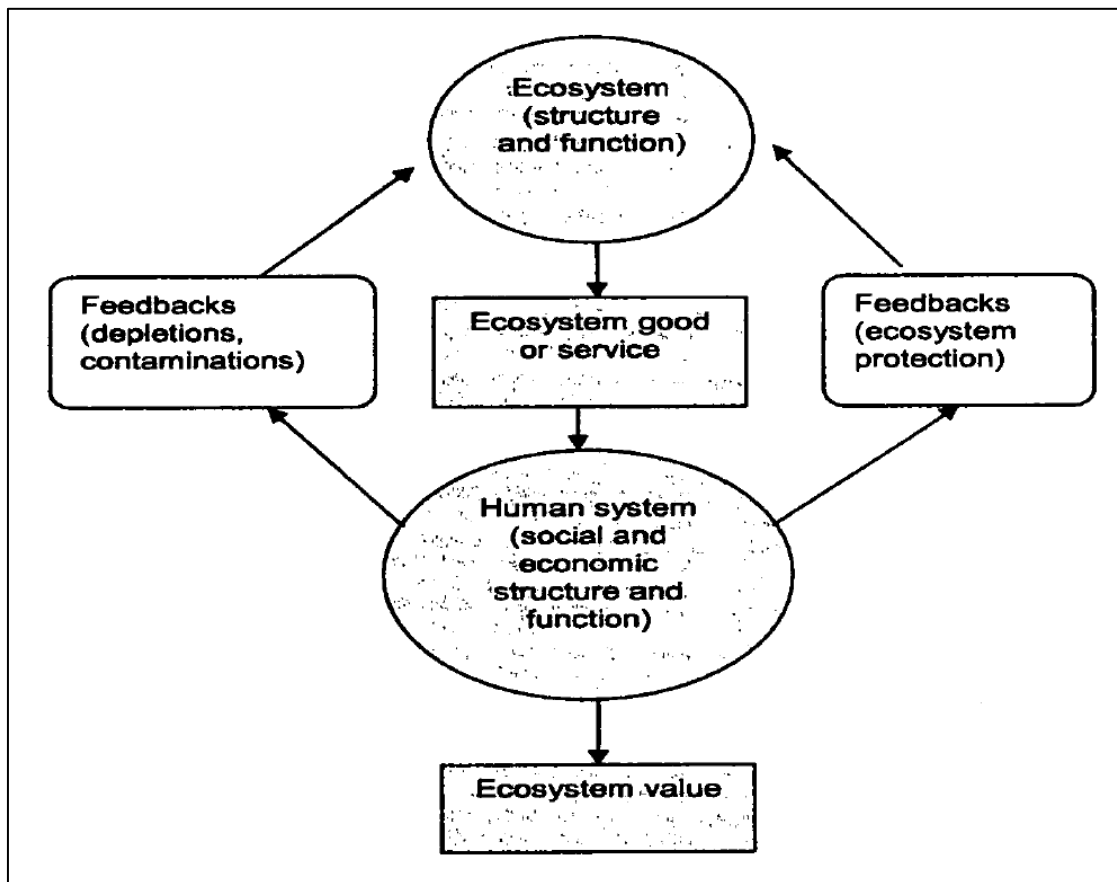


Figure 8: The cycle of ecosystem services in a socio and economic model. Retrieved from: Brown *et al.*, 2007

As previously discussed, there are many sustainable and regenerative practices that are widely recognized, but the question remains, why are farmers not adapting them. Cultural norm, education, and access to technology play a part, but research shows that the main barrier of change towards sustainable practices is the economic cost. For example, Robertson (2015) discussed that glyphosate-resistant soybeans which permitted the substitution of a less toxic herbicide (glyphosate) for ones that are both longer lived and more toxic and mobile in the environment, achieved over 90% adoption rates over the course of 10 years by farmers in the United States. On the other hand, continuous no-till practices have been feasible for more than 30 years but is only used on 12% of United States corn crops. Swinton (*et al.*, 2015) asked farmers located in Michigan, United States why they are not adapting sustainable practices like no-till. They discovered that farmers are likely to adapt those practices known to benefit the environment only if they saved on labor, inputs, or improved farmstead health without decreasing crop revenue. The researchers also discovered that nearly all farmers, especially those who managed large farms were willing to accept payments for adopting specific strategies. Interestingly, another

discovery made was that the farmers were willing to accept less payment for practices they believed would provide benefits close to home. For example, adapting practices that build soil organic matter which reduces nitrate leaching would require lower payments than practices that reduce GHG emissions, which is considered more of a global problem (Robertson, 2015). It's clear that farmers value the environment and would prefer to use sustainable practices, but sustained profitability is an overriding problem.

There may be an increased incentive for farmers, policy makers and stakeholders by integrating this new soil organism-based knowledge with public health experience. Researchers would be able to apply soil-based approaches and policies to control current and emerging infectious diseases, water quality, and food security issues. These sustainable and regenerative practices imply a holistic approach which could create a platform for operating more closely with producers. This could potentially increase the knowledge sharing about soil biodiversity and soil biological processes through farmer-to-researcher and farmer-to-farmer networks.

CONCLUSION

Our earth is losing soils and its diversity at a rapid rate, with considerable harmful ramifications on the health of the public globally. We need to recognize and manage soil biodiversity as an underutilized resource for achieving long-term sustainability goals related to global public health, not only for improving soils, food security, disease control, water quality, but because soil biodiversity is connecting to all life and provides a broader, fundamental ecological foundation for working with other disciplines to improve human health (Wall *et al.*, 2015).

This literature review discussed two approaches to the application of soil biodiversity and public health knowledge in agricultural systems: a reductionist and a holistic approach. The reductionist one is based on maximizing yield and inherently ignoring soil organisms resulting in the negative feedback loops, making this approach unsustainable. Whereas the holistic approach consists of managing soil ecosystems and their diversity in favor of their multifunctionality, and considers the complementarity, complexity and self-regulation of soil biota and plant-soil biota interactions (Mujtar *et al.*, 2019). This paper acknowledges that soil biota provides many benefits, even if those benefits are not easily observed and that the loss of soil biodiversity in agricultural settings has many negative impacts that reach far beyond the point of disturbance.

Rather than focusing exclusively on the relationship of crop yields and soil biodiversity, this review examined the role of soil health and soil biodiversity to public health while considering the three pillars of sustainability: environmental protection, social equity, and economic viability. Economic viability was found to be the root cause of the continuation of conventional agricultural practices which in turn has caused the degradation of soil and soil organisms, as well as many ecosystem services provided by the soil and its diversity. It's time to understand that soil organisms are a critical element in the process of life, which needs to be nurtured and increased. It has been said, with no exaggeration that soil is the “fragile, living skin of the Earth”, yet both its aliveness and fragility have all too often been ignored in the expansion of agriculture across the face of the globe (Rhodes, 2017).

RECOMMENDATIONS

- **Researchers**

There is an abundant amount of information on how soil organisms increase soil health, food production and ecosystem goods and services, but in general there is still a lot of knowledge lacking about soil organisms. Soils hold one of the largest reservoirs of microbial diversity on earth (Bell, 2016), and much of it is not discovered. These organisms and their interactions may hold answers to many of the world's problems, such as public health and food production, as was discussed in this literature review. It should also be noted that soil biodiversity, much like soil itself, is highly variable across fields and regions. This highlights the need to understand how soil communities are organized in complex soil food webs, which differ spatially across global regions (Wall *et al.*, 2015). The biggest challenge to develop sustainable agricultural systems is integration, according to Robertson (2015). Meaning that farms must be sufficiently understood, which would give the whole picture of how a change in one part will affect others and ultimately deliver ecosystem goods and services. Currently we lack this understanding. To obtain this knowledge, a systems approach is required for ecological questions and a socioecological approach to comprehend the factors that affect management decisions. Acquiring this knowledge could help to move us forward toward the adoption of sustainable practices, maybe more quickly than the usual piecemeal approach, which in the past has often led to environmental issues and unwanted surprises. The lack of knowledge of soil biodiversity was a limitation for this literature review, thus, more research and developments need to be made in order to have a clear picture

of the role of soil biodiversity, its benefits to sustainable and regenerative agriculture, and its impacts on human health.

As previously discussed in the Soil Health and Soil Biodiversity section, soil organisms are useful indicators of soil health. They are well correlated with soil functions and processes, sensitive to land-use and climate changes and are good teaching tools due to elucidating ecosystem process. Although, the technology to assess the diversity is not feasible or useful for farmers. When and if measurements are made there is a plethora of information, but it may not be useful for farmers in the sense of how they should change their practices. Developments need to be made for soil biodiversity measurements that are meaningful, accessible, and useful for land managers.

- Policy Makers, Investors, and other stakeholders

Many people blame the farmers for agriculture's role in degrading the environment, this should not be the case. As discussed previously, they need to not only meet demands but also make enough revenue for themselves. Even though most farmers appreciate and understand the need for environmental conservation, the simple fact remains that the economic survival and viability are the primary goals of land managers. When it boils down to market demand for low-cost produce and society's demand for a healthy environment, farmers are caught in the middle. Changing their practice to be more sustainable is a high personal risk. The change must be economically viable, but research shows that most forms of sustainable practice that increase soil biodiversity is not viable for farmers. Then the main barrier to farmers' adaptation of more sustainable practices becomes the absence of economic incentives. The sustainable practices that enhance soil biodiversity for the optimization of crop production and human health should have incentives that should be incorporated into policies that are integrated with public health and food security in government and global organizations such as the World Health Organization (WHO). Incorporating soil organisms into policies may create a discussion and incentives with a holistic approach towards sustainable agricultural production. However, incentives such as carbon banks for farmers as a part of a plan to combat climate change in the United States have caused social inequity. It has made farmland more valuable, which has hindered access to land especially for minority groups. Without a strong equity component then, climate-farming schemes are likely to worsen social inequity and consolidate land ownership—factors that are correlated, in turn, with environmental degradation (Fassler, 2021). Lastly, outside of public institutions and government policies and incentives, regenerative and sustainable agriculture need outlets to

communicate their financial needs to the investment community, which varies depending on scale, corporate form, and location (Electris *et al.*, 2019). Farmers partnering with investors may stimulate positive social and environmental benefits and impacts that sustainable and regenerative forms of agriculture hold. For agriculture to be sustainable, it must be economically viable, which may only be possible in the form of incentives, policies and investors. However, paternalism should be avoided so farmers have freedom on the management of their land. I recommend farmers to collaborate with multiple local organizations to coordinate efforts, as well as start small to build abilities and confidence to decrease the financial risk. As more research is developed, showing the benefits of regenerative and sustainable agriculture may inspire increasing involvement and participation.

- Farmers

Once sustainable strategies are economically viable there are a lot of practices farmers can adapt to increase the soil biodiversity. As previously discussed, farmers are not to blame but complete successful development and implementation can only be accomplished with the producers, who are the primary stewards of the land. As seen in Table 3, the strategies for sustainable management optimize the benefits of natural cycles through the interactions of soil organisms, which reduce the dependence on non-renewable resources and can help producers identify and understand long-term goals for sustainability that can also possibly meet short-term needs for production. Farmers need to stay relevant and contribute to discussions of upcoming information since they have the ultimate say in what happens to their land.

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