A report for:

Regenerative farming practices and their impact on the soil health

by Marcin Markowicz,

2023 Nuffield Scholar, Poland

December 2024

Nuffield International Project No 43

Supported by:

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Executive Summary

Intensive farming, geared towards maximising yields and profits through the extensive use of synthetic inputs and agro-technical simplification, has a significant negative impact on the chemical, physical and biological properties of the soil. The dominance of cereals in the sowing structure, reaching up to 80%, leads to species erosion in crop rotations, which reduces biodiversity and decreases humus content. As a result, the soil loses its buffering capacity, crucial in the face of extreme weather events such as droughts, heat or downpours.

Conventional cultivation, sowing, fertilisation and crop protection technologies often do not take into account local field conditions, leading to reduced effectiveness of measures to improve soil quality and increase soil biological activity. In particular, the untapped potential of crop residues, limited incorporation of organic matter from intercrops and insufficient support of soil biological life by fertilisers are significant challenges. In addition, changing regulations, including the withdrawal of commonly used active substances, confront farmers with the need to adapt to new realities. This requires the acquisition of knowledge, the implementation of innovative technological solutions and practical experience to manage effectively under changing conditions.

This report presents my experiences and observations gained during my Nuffield journey, demonstrating global regenerative agriculture practices and their impact on soil health. I describe key principles and methods such as minimising tillage, using intercropping, soil analysis, crop diversity, enriching the soil with organic matter and integrating agroforestry and animals into farming systems.

The conclusions show that regenerative agriculture can significantly improve soil structure, increase water retention capacity, promote biological activity and reduce the need for chemical fertilisers and pesticides. I recommend the gradual implementation of these practices through education, planning, systematic monitoring and adaptation of activities.

The transformation towards regenerative agriculture responds to the challenges of soil degradation, climate change and increasing economic pressures. Adopting these practices promotes yield stability, environmental protection and sustainability, laying the foundation for the long-term sustainability of agricultural systems.

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Foreword

My interest in agriculture has its roots in my childhood, spent on my grandparents' farm, where I observed the daily toil of farm work. As I grew up, I became more and more involved with the family farm of 28 hectares, which was run by my Dad in Czerwonkow. My interest in crop technology, particularly soya, which became my main specialisation in later years, grew with my experience. After finishing primary school in Baborow, my home town, I decided to attend a secondary school with a specialisation in mathematics and information technology, but I knew even then that I was going to continue my studies in agricultural studies after my matriculation.

Studying agriculture, which I graduated from in 2013, allowed me to explore agronomy and develop my passions. During my studies, I did an internship on a large-scale modern farm, which was a dream come true and a great experience for me. After graduation, I started working at Top Farms Głubczyce, where I took up the position of agronomist responsible for growing cereals, oilseed rape, seed grasses, and soya. At the time of my employment, soya was still a new crop in Polish agriculture, and my knowledge of it was limited. I decided to take up this crop by getting involved in soybean projects to develop suitable cultivation technologies for Polish conditions.

Thanks to the experience gained and participation in numerous projects, a comprehensive soybean cultivation technology was developed in Poland, enabling high yields to be achieved. As a result of the research and development activities carried out, significant progress has been made in registering suitable plant protection products and soybean varieties. Polish farmers are now able to cultivate this crop with increasing success. The area under soybean cultivation in Poland is increasing year by year, and yields are improving. My fascination with soybean cultivation and extensive experience in cultivation technology led me to conduct scientific research in the field of soybean cultivation systems. In 2019, I defended my PhD thesis entitled *'Influence of cropping systems on the development and yield of soybean (Glycine max (L.) Merrill) varieties'.* My scientific work provided an even deeper understanding of the specifics of soybean cultivation and its adaptation to Polish soil and climatic conditions.

As an agricultural enthusiast, I am a member of the provincial team of the State Experimental Variety Experimentation, the team for stabilisation and market support for hops, tobacco, legumes, and seed crops at the Ministry of Agriculture. I am also a member of the programme board of the Terra Nostra Foundation, whose primary objective is to support farmers and processors by disseminating best practices and solutions in soil, plant, and food production.

During my work as an agronomist, I have had the opportunity to meet many interesting farmers. One of them who impressed me the most was Gary Zimmer from the state of Wisconsin—a pioneer of organic farming in the USA. In 2018, I had the pleasure of visiting his farm, which made me think a lot about how to grow crops. Upon my return, I was convinced that we needed to change our approach to soil analysis, fertilisation, cultivation, intercropping, and reducing the use of pesticides, particularly glyphosate. I strived to acquire new knowledge, spending a lot of time exploring, analysing, and putting it into practice in my own fields.

The first elements I began to modify were greater attention to soil testing and fertiliser planning, where I sought to understand and test the importance of the balance of minerals in the soil that Gary talked about. I also started changing my approach to tilling the soil, adopting the principle of *"as little as possible, but as much as necessary."* Using intercropping and learning to select species for seeded mixtures was another step towards positive change in my fields.

Inspired by these experiences, I decided to explore the topic of regenerative agriculture around the world—to find out how other farmers understand the concept, what practices they use on their farms, and which ones could be adapted to Polish climatic conditions. Therefore, I decided to apply for the Nuffield International Scholarship as the first scholarship holder from Poland.

Figure 1: Author, Marcin Markowicz (source: Author)

My study travel

My Nuffield journey was over 100 000 kms long, between the Global Focus Program and my personal travels. I travelled for my project through the Canada, New Zealand, Indonesia, Japan, Australia, Brasil, USA, Canada, Germany, Netherlands, Austria, United Kingdom and Romania. I visited arable farmers, organic growers, regenerative farms, agroforestry farms, convencional farms and also vegetable growers. During farm visits, I spoke with farmers to understand how they define regenerative agriculture and what specific methods they use on their farms. I focused on soil analysis, soil cultivation, the use of natural fertilizers and compost, and the selection of intercropping species used in these practices.

Table 1: Study travel

Travel date	Location	Visit/Contacts
March 7^{th}-17^{th}, 2023	Canada: British Columbia Vancouver Island	Pre-Contemporary Scholars Conference tour Contemporary Scholars Conference tour
March 20^{th}-23^{th}, 2023	New Zealand: Wellington	Pre-Triennial Tour
March 24^{th}-1^{th} April, 2023	New Zealand: Christchurch to Qeensland	Nuffield International Triennial Conference
April 2^{th}-$6^{th,}$ 2023	Indonesia	GFP
April 7^{th}-$15^{th,}$ 2023	Japan	GFP
April 16^{th}-$22^{th,}$ 2023	Australia	GFP
June 18^{th}-23^{th},2023	Austria: Vienna	Word Soybean Research Conference
August 6^{th}-12^{th}, 2023	Brasil: Formosa Fromoso Jaborandi Fazenada	Anna Carolina Zimmermann, Nuffield Scholar. Samuel Vinicius Desconzi, Farmer, Fazenda IPE farm. Sally Thomson, CEO Nuffield Brasil
August 13^{th}-25^{th}, 2023	USA: Pensylwania North Carolina Kentucky Missouri Kansas Iowa Wisconsin	Laura Kilian NSch, Agricultural Science Center: Steve Troxler. NC Agronomics Lab: Dr. Hudak-Wise Plant Science Building, NC State University: Dr. Percy and Dr. Vann Kornegay Farms: Kim Kornegay Coastal Carolina Cotton Gin Griffin Farms, Archie Griffin NSch Frahm Farmland: Lon Frahm, CEO Gary Zimmer: Organic Farmer

		Precision Planting Center – two-day training.
August 26th- September 1th, 2023	Canada: Qubec	Odette Menard NSch. Progrian ZIA: Philippe Lemaitre, Technical manager of seed.
April 7th-13th, 2024	Germany	Meinke Ostermann NSch, Family Farm Roman Kurzer: farmer Dag von Kap-herr: farmer Stefan Knittel: potato farm Jan Grosse Kleimann- Regenerative farmer Nexat: Benedikt Pohl Holtkotter Agrar: Marcus Holtkotter Wili Kremer-Schillings -Journalist, farmer Alexander Schierholz-Prilop; No-till Farmer
April 14th-19th, 2024	Netherlands	Linda Kopczyński NSch, Edwin Smits NSch, Lotte van Dueren NSch, Diana van Veelen NSch- Dairy farm Rogier Scherpbier NSch, Zonnespelt Farm Bart Grobben farm: arable farm and soybean Bio Brass Aeres Hogeschool Dronten
June 17th-22th, 2024	United Kingdom	Greens of Soham; Will Shakeshaft, Gregg Colbrook. Dyson Farming; Ben Abell South Ormsby Estate, large organic estate, Paul Barnes. Toby Simpson NSch: Farmer Stephen Briggs NSch: Organic farm and Agroforestry. Houghton Hall – Evolution farming, Tom Rwason NSch, Manager Ollie Crottie. Holkham Hall Estate and farms: Poul Hovesen, James Beamish, harry Barnett NSch, Dominic Swann. G's Fresch engine Farm: Julius Joel

July 29th- August 1th, 2024	Romania: Nanov	Agrinatura Group

Acknowledgments

I would like to extend my heartfelt thanks to my sponsor, Top Farms Group, for giving me the opportunity to undertake this extraordinary scholarship.

I am deeply grateful to my wife, Marzena, and my daughters, Lena and Laura, for their perseverance during my absence from home, as well as for their immense support and faith in me while I gained new life experiences. I also thank my parents and in-laws for their help and support for me and my family during my travels.

I would like to express my gratitude to all the Nuffield Scholars who hosted me during my journeys, dedicated their time, and shared their knowledge, experiences, and insights into agriculture in their regions.

Finally, I extend my thanks to Nuffield International for the warm welcome and support I received as the first Nuffield Scholar from Poland.

Objectives

The purpose of this report is to:

- Define regenerative agriculture on a global scale.
- Characterize regenerative agriculture practices and their impact on soil health.
- Outline a pathway for transforming a conventional farm into a regenerative farm.

Chapter 1: Introduction

When I started taking an interest in my father's work on our farm about 25 years ago, and later began working at Top Farms, I noticed how rapidly agriculture was changing. The first and most rapid change was the mechanization of field work. My childhood memories of working with horses on the farm contrast with the experiences of my youth, when I learned to cultivate the soil with a tractor and modern machinery. Today tractors are equipped with advanced systems, electronics, computers and navigation systems, and operators must have the knowledge of how to use them effectively.

An equally dynamic change that I remember well was the development of the use of crop protection products. In the beginning it was mainly herbicides, but as the years passed, new active substances and agents from different groups, such as fungicides, insecticides and growth regulators, appeared on the market. Farms grew rapidly, and with this grew a dependence on chemistry to provide easy solutions to problems. The rapid development of equipment and the intensive use of chemical pesticides caused many farmers to forget the basic principles of agricultural practices, which should cooperate with nature and the soil.

As a result, I was beginning to look for answers to the question: what is regenerative agriculture, which is becoming increasingly popular around the world, really? Is it really a new era in agriculture or just a trendy slogan?

History of regenerative agriculture and definition

Regenerative agriculture, although a relatively new term, is based on principles practised by generations of farmers who have cared for the land in a sustainable and responsible way. Its history is closely linked to the search for ways to improve soil quality, preserve biodiversity and sustainable agricultural production.

There are several movements behind the term regenerative agriculture. The term was coined by Robert Rodale - son of J.I. Rodale, one of the pioneers of organic farming in the United States in the 1930s - who later founded the Rodale Institute, which researches and promotes regenerative agriculture. Permaculture, an approach to agriculture that mimics patterns found in nature and which has long been used by indigenous peoples around the world, is another movement that is sometimes considered a form of regenerative agriculture.

Alexander Schierholz-Pirlop a German farmer who runs a regenerative farm in integration with livestock production and agroforests points out that regenerative agriculture is not the same as organic or conventional agriculture, but is a separate model that focuses on soil restoration, increasing biodiversity and combating climate change.

According to Gary Zimmer, who runs an organic farm in the state of Wisconsin, regenerative farming is a way of managing a farm that promotes soil life, efficient use of nitrogen, reduced use of chemicals and the production of healthy, high-yielding crops. In practice, this means that nurturing healthy, mineralised soil is key, as this translates into healthy plants that are disease resistant and of higher quality.

Each approach to regenerative agriculture has slightly different assumptions, particularly depending on where in the world it is applied. Common principles include practices such as; minimum tillage, use of intercropping, soil analysis, use of natural and organic fertilisers and mechanical and biological methods to control weeds, diseases and pests first.

Today, regenerative agriculture is seen as the answer to several global challenges: climate change, loss of biodiversity, soil and water pollution and the food crisis. Regenerating soil, increasing its carbon sequestration capacity and producing healthy food are goals that are attracting increasing attention from farmers, consumers, non-govermental organisations and politicians.

Good farm management means taking concrete action in areas where farmers have influence. Although they cannot control the weather, they must adapt their operations to changing weather conditions. Nor can they replace the soil, but they can take steps that promote soil health and microbial life. Whatever the soil type - sandy, clayey - it is possible to introduce measures to improve the quality of the soil, e.g. by changing the crop rotation, adding new plant species or sowing intercrops. It is important for farmers to control access to air and water for the roots, balance minerals, ensure maximum soil cover and manage fertilisation correctly.

Although farmers have access to a wide range of synthetic fertilisers and crop protection products, in many cases their use is irrational. Using fewer chemicals and more natural fertilisers is the key to improving soil fertility. The right distribution of nutrients at the right time and in the right form, attention to trace minerals, calcium, the development of root systems, healthy plants and plump, fertile soils are all elements that contribute to increased yields and improved plant quality.

Most farms in Europe operate in a traditional farming way, while implementing a number of practices specific to sustainable agriculture. One of the most popular practices is the abandonment of ploughing in favour of no-till methods and strip-till technology. Intercropping is common on these farms and, where organic fertilisers are available, farmers try to use them to improve soil fertility.

For many farmers, the implementation of these practices stems from their awareness and belief in the beneficial effects on the soil, particularly in terms of building organic matter content. Nevertheless, some producers acknowledge that the use of these practices is primarily the result of European Union regulations related to the implementation of ecoschemes and the possibility of obtaining subsidies.

Fertile and healthy soil

Soil fertility is the ability of the soil to provide plants with the necessary nutrients in adequate amounts, which allows them to grow and develop properly. Fertility depends on several factors, such as mineral content (e.g., nitrogen, phosphorus, potassium), physical properties (e.g., soil texture), and biological processes in the soil (microorganism activity). High soil fertility means high agricultural productivity, while nutrient-poor soils are less fertile (Gorka 2016). Nichols (2018) defines healthy soil as the ability of the soil to support functioning, life-sustaining, healthy plants, animals and people.

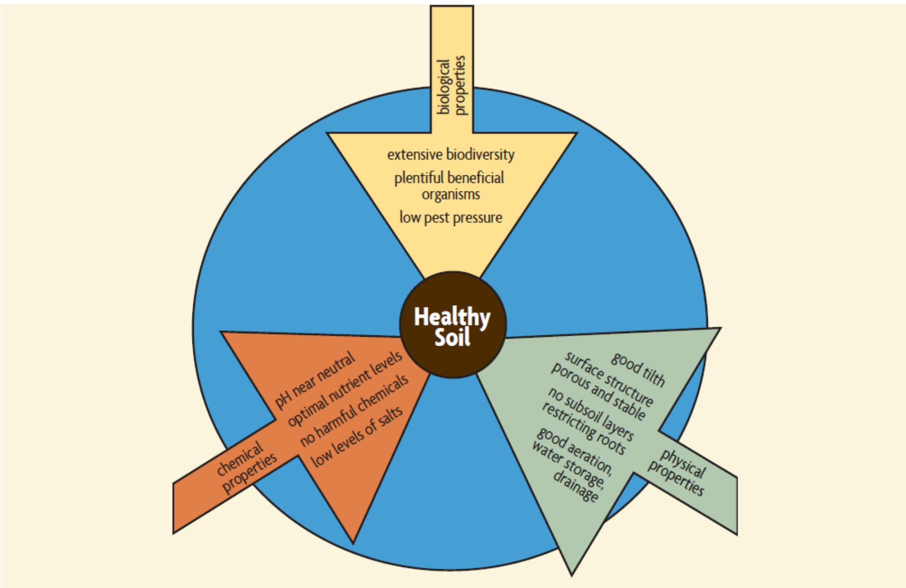

Figure 2: Optimal chemical, biological, and physical properties promote healthy soils. Source: Building soil for better crops, (Source: Magdoff, 2009)

Chapter 2: Key principles and practices in regenerative agriculture

These principles are based on observations of the natural ecosystem and how soil is managed in nature to maintain the balance and services required to support healthy plants. The principles are as follows:

Change of thinking

Understanding and accepting the philosophy of regenerative agriculture is the first step toward change. The best way to make a successful transition to regenerative agriculture is to learn from those who have already implemented these practices, and then use trial and error, making changes in your own fields, learning on your own.

Above all, it's about changing the way we think - about looking at the land not as a resource to be exploited, but as a living organism that needs to be cared for and nurtured for its health and balance. Instead of focusing only on maximizing yields and profits in the short term, regenerative agriculture promotes sustainability, which takes into account the long-term well-being of the soil, biodiversity and ecosystems.

The farmer becomes more aware of the role played by soil organisms, plants, animals and microorganisms in creating a healthy environment. Central to this approach is attention to biodiversity and ecological balance, which contributes to soil restoration and long-term fertility. Farmers I visited during my research trip unanimously stressed that the key is the conviction to make changes and the consistency to implement them. While visible results may appear relatively quickly, the real effects take time and pay dividends over the long term.

Test and balance your soil

Good soil is not just a mass of minerals, it is a living thing, with minerals, water, air, organic matter, and the organisms that turn organic matter into humus and convert minerals into plant-available forms.

The basic principle is to know if your soil is lacking nutrients, as any nutrient deficiency becomes a limiting factor in yield and quality and potentially triggers weeds, diseases and pests. There are many different types of soil tests, basic P, K and pH to full soil minerals, penometric soil compaction tests and many types of soil microbiological tests that measure the amount of different types of soil life (bacteria and fungi).

When assessing the condition of the soil, it is important to trace the history of the fields, the record of tillage operations and the use of pesticides, and then assess the properties:

1. **Chemical**

- Is there a complete soil test (organic matter, CEC, major elements, trace elements, basesaturation)?

How often were soil tests taken in the past?

- Liming practices - has it been done? If so, what type of lime was used?
  Was liming based on pH or on nutrient needed?
- Fertilizer practices - how much was used and what was the source?
  Was only N-P-K used? What source?
  Other fertilizer materials used -sources?
  Amount of nitrogen used - source?
  Manure or compost used - how was it applied and in what amount?
- Pests - are insecticides used? Fungicides?
  Insect pressure and species?
  Fungal diseases? What kinds and how often?
- Weeds - are herbicides used? What type and what amount?
  Weeds types and pressure?
  Is the weed pressure uniform, or are there areas with more weed problems than others?

2. Physical

- Tillage practices, type of tillage, what tools, when, amount?
  Do you strip or zone till?
  Has subsoiling been done?
  Is vertical tillage a part of the farm? No till?
  Are row crops cultivated?
  Are there row units or tillage practices done at planting?
  How many trips over the field?
  Is compaction watched or a concern ?
- Crop management practices
  Are residues incorporated into soil? How? Disked or chopped in small pieces?
  Are only row crops grown?
  Are crops rotated? How often?
  Any livestock manure - how is it used?
  Any green manure or cover crops?

3. Biological

- Soil life - is it healthy?
  Are earthworms present? Have there been more or fewer earthworms in the past?
  Does crop residue decay rapidly and completely?
  Does water infiltrate quickly or is it forming puddles?
  Have there been any soil biological tests?
- Organic matter:
  Are residues present deep in the soil? Are they moldy?
  Has the soil always had a nice, earthy smell?
  Are your organic matter levels increasing or decreasing?
- Pests
  Are there insect and disease problems with the crops? What and when?

Have insects types changed over the years - what major insects are now present?

- Crops - what crops were grown? How were they managed?
  What was the rotation? Any cover crops?
  What fertilizers were applied? How did they impact yield?
  Any crop problems? Did the plants have a healthy root system?

Soil testing and analysis aims to provide information that cannot be ascertained through organoleptic assessment.

A key element of the modern approach to assessing the quality of nutrient supply to soils is the analysis of the sorption complex of soils, referred to as the *Cation Exchange Capacity* (CEC). The next step is to determine the degree of saturation of the sorption complex with base cations, expressed as the percentage of base cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) in the total cation exchange capacity (CEC).

Optimal levels of minerals in soil are commonly based on the research of soil scientist William A., who proved that declining soil fertility, identified by a lack of organic matter, is due to an imbalance of major and trace elements. According to Albrecht (1975), the cations in the soil must be in a certain ratio for plants to have easy access to them.

Neal Kinsey, in his book 'Hands of Agronomy' (1993), defines the ideal ratio of soil cations as:
- 60-70% calcium
- 10-20% magnesium
- 3-5% potassium
- 1% sodium
- 10-15% hydrogen
- 2-4% other cations

The percentage of saturation with the base cations calcium, magnesium, potassium and sodium, as well as the relative proportions of these cations, provide a measure of the soil's ability to retain and release various elements and chemical compounds, particularly positively charged nutrients. The capacity of the sorption complex can be figuratively compared to the size of a vessel: soils with a high CEC are like large buckets, while soils with a low CEC resemble small buckets.

Sandy soils, characterised by a low organic matter content, usually show a very low CEC. In contrast, clay soils, which contain higher amounts of organic matter, especially in the form of humus, are characterised by high CEC. Such properties affect the soil's ability to store nutrients, which is crucial for effective soil fertility management.

Organic matter

The organic matter content of agricultural topsoil is usually in the range of 1–6%. A study of soils in Michigan demonstrated potential crop-yield increases of about 12% for every 1% organic matter. (Magdoff, 2009). It follows that organic matter plays a key role in soil fertility and quality.

Allison, in his book Soil Organic Matter and Its Role in Crop Production (1973), refers to organic matter as ‘the key to soil fertility and productivity’. Similarly, Dr William A, in The Albrecht Papers (Vols. I-VII), calls it ‘the constitution of the soil’. Organic matter is a complex set of materials and processes that integrate the three basic properties of soil: physical, chemical and biological.

It is not a homogeneous material, but a dynamic mixture of substances that can be divided into four main categories:

1. Living organisms - the entire soil microbial community, including earthworms, protozoa, arthropods, bacteria, fungi, etc.
2. Recently dead and incompletely decomposed plant and animal residues - these include animal manures, crop residues, old roots and green manures. These materials still retain the characteristics of their original sources, such as plant stems or roots. Under moist conditions, they decompose under the influence of micro-organisms (bacteria, radicles, fungi) and earthworms.
3. More decayed materials - include residues in an advanced stage of decomposition.
4. Decay - the most decomposed form of organic matter, characterised by its dark brown or black colour and lack of visible stem or root residues. Decay is a complex mixture of the chemical building blocks of soil.

Organic matter not only influences yield but also integrates key soil processes, making it essential for soil function and renewal.

Fertilization

The right choice of fertiliser, taking into account salt and ammonia levels, is crucial to maintaining soil health and plant growth. Fertiliser selection should be guided by the chemical composition of the fertiliser, preferring formulations with balanced nutrients, ranging from fast-soluble to slow-release, pH-controlled formulations.

Based on the results of the soil analysis, indicating possible nutrient deficiencies or excesses, it is necessary to apply soil improvement sources to restore soil balance and to select fertilisers that will optimally feed the crop. Particular attention should be paid to the presence of undesirable elements in fertilisers. Examples are chlorides, found in potassium chloride which can adversely affect the development of the root system and the life of micro-organisms in the soil.

Another important parameter is the salinity index of the fertiliser. A high salinity level can restrict the development of young roots and have an adverse effect on soil microflora. It is recommended to use fertilisers with a salt index below 100, which minimise the risk of harmful effects on soil life and provide more favourable conditions for plant development (Zimmer, 2011).

Tabel 2: Salt index of the fertilizer, source: Advancing biological farming. (Source: Zimmer, 2011)

Fertilising material	**Salt index**
Potassium chloride	116
Ammonium nitrate	105
Sodium nitrate	100
Urea	75
Ammonium sulphate	69
Calcium nitrate	53
Potassium sulphate	46
Sodium chloride (table salt))	154

When choosing fertilisers, it is important to consider their effect on soil pH. Some fertilisers have an extremely high or low pH, which can significantly disrupt the soil's microbial balance. For example, the pH of ammonium phosphate (DAP) ranges from 9 to 11, which is well beyond the optimum soil pH range of 6.5-7.0. Applying a fertiliser with a pH as high as 11 can alter the composition and activity of soil organisms at the site of application, negatively affect nutrient availability and interfere with healthy trichome development.

It is recommended to use naturally mined fertilisers, which have a less processed chemical composition. Such raw materials, which are not intensively treated, contain trace amounts of micronutrients such as cobalt and molybdenum. Although these elements are not considered essential for basic plant growth, they play an important role in plant-soil interactions, contributing to the health and productivity of the soil ecosystem.

Naturally extracted fertilisers also have lower solubility, ensuring a gradual release of nutrients into the soil. This property reduces the risk of their leaching during heavy rainfall and ensures a long-term supply of minerals to the soil. As a result, these fertilisers help to maintain the balance of the soil environment and promote stable crop development.

Crop protection

In regenerative agriculture, the use of herbicides, insecticides and fungicides should be limited to situations where it is absolutely necessary. Substances of this type have no beneficial effect on the soil and their use is indicative of existing problems of poor soil quality and sub-optimal environmental condition. Although they may be necessary in some cases, the regular use of these products does not promote long-term improvement in soil health and plant health.

As the soil regenerates and its biological activity increases, the need for pesticides and nitrogenous fertilisers decreases. Most plant protection products carry negative side effects on both the soil and the crop. Each chemical treatment should be carefully considered and biological or mechanical alternatives should be considered first. Pesticides may be effective in solving a problem in a given season, but their use can lead to long-term negative effects, such as reduced crop resistance in subsequent years.

It should also be emphasised that the effects of herbicides, insecticides and fungicides on soil microorganisms, including nitrogen-fixing bacteria and arbuscular mycorrhizal fungi, are not yet fully understood. These organisms play a key role in maintaining soil health and productivity. Therefore, the use of chemical plant protection products should be limited and treated as a last resort, and the main goal of regenerative agriculture should be to seek to naturally enhance the soil ecosystem and reduce the need for agricultural chemicals.

Weed control

Soil contains significant amounts of weed seeds, which can remain capable of germinating for decades - in some cases as long as 40-50 years. The germination of weed seeds depends on specific environmental conditions, such as low oxygen levels and high carbon dioxide content in compacted or moist soils. Other factors that initiate germination are soil agitation and exposure of seeds to light. In addition, weeds often show the ability to germinate at lower temperatures than crops such as maize or soya, giving them a competitive advantage early in the growing season.

The decision to control weeds should be based on the potential yield loss or reduction in quality that they can cause. Completely removing weeds merely for the aesthetic effect of a ‘clean field’ is an inefficient use of resources. Of key importance here is the ‘economic threshold’, defined as the level of weed infestation that has a significant impact on the crop. The value of this threshold varies according to weed species and crop.

The effectiveness of weed control largely depends on the right timing. The most effective time is during the early stages of weed growth (the so-called ‘white root stage’), when weeds are most susceptible to destruction. For weeds germinating in cooler conditions, it is worth allowing them to pre-sprout and then destroying them during seed-bed preparation.

In situations where weeds have germinated, they should be destroyed before seed production to prevent further spread. Some weed species are more susceptible to destruction at the flowering or seed production stage, when their reserves in the roots are lowest. By using these strategies, weeds can be effectively controlled, minimising their impact on crop yield and quality.

Weed resistance to herbicides in GM crops: cases in the USA and Brazil

One of the key challenges in genetically modified (GM) crops is the problem of weed resistance to herbicides, especially glyphosate. The widespread use of this herbicide in GM crops such as soybean, maize and cotton has led to the selection of resistant biotypes, making control significantly more difficult and forcing farmers to implement more complex weed management strategies (Heap, 2023).

Figure 3: Resistance of white quinoa to herbicides, USA. (Source: Author)

In the United States, one of the most difficult weeds to control has become rough amaranth (*Amaranthus palmeri*). The resistance of this species to glyphosate has been confirmed in many states, particularly in areas of intensive soybean and cotton cultivation (Owen, 2008). Ragweed, with its ability to grow rapidly and its high seed production, poses a serious threat to crop yields. Another problematic weed is Canada adjective (*Conyza canadensis*), which first showed resistance to glyphosate in 2000. By 2012, resistant biotypes had spread to more than 25 million hectares of arable land in the USA, necessitating the use of more diverse crop protection methods (Mortensen et al., 2012).

Similar challenges exist in Brazil, where the intensive use of glyphosate in GM crops has led to the selection of resistant weed biotypes. An example is rigid ryegrass (*Lolium rigidum*), which is becoming increasingly difficult to control in cropping systems (Carvalho &

Christoffoleti, 2008). Rough amaranth (*Amaranthus palmeri*) is also spreading in intensively farmed areas, posing a serious challenge to Brazilian farmers (Heap, 2023).

Weed resistance to glyphosate highlights the need to develop sustainable weed management strategies. Herbicide rotation, the use of agents with different mechanisms of action, and the integration of mechanical and biological methods are essential to reduce this problem (Powles & Yu, 2010). The introduction of such strategies aims to reduce selection pressure on weeds and to reduce the negative ecological and economic impacts associated with weed resistance.

Magdoff (2009) provides examples of natural ways to reduce disease, pest and weed pressure in his study:

- Adequate nutrient levels reduce disease incidence. For example, calcium applications have reduced diseases in crops such as wheat, peanuts, soybeans, and peppers, while added potassium has reduced the incidence of fungal diseases in crops such as cotton, tomatoes, and corn.
- Damage from insect and disease (such as fungal diseases of roots) can be decreased by lessening soil compaction.
- Severity of root rots and leaf diseases can be reduced with composts that contain low levels of available nitrogen but still have some active organic matter.
- Many pests are kept under control by having to compete for resources or by direct antagonism from other insects (including the beneficials feeding on them). Good quantities of a variety of organic materials help maintain a diverse group of soil organisms.
- Root surfaces are protected from fungal and nematode at-tack by high rates of beneficial mycorrhizal fungi. Most cover crops help keep mycorrhizal fungi spore counts high and promote higher rates of infection by the beneficial fungi.
- Parasitic nematodes can be suppressed by selected cover crops.
- Weed seed numbers are reduced in soils that have a lot of biological activity, with both microorganisms and insects helping the process.
- Weed seed predation by ground beetles is encouraged by reduced tillage and maintenance of surface residues. Reduced tillage also keeps the weed seeds at the surface, where they are accessible to predation by other organisms, such as rodents, ants, and crickets.
- Residues of some cover crops, such as winter rye, produce chemicals that reduce weed seed germination.

Case study – crop protection

The use of biological products in Brazil as well as internationally is also becoming more and more common. Samuel Desconzi has set up a micro-factory on his farm to propagate bacteria and apply them to his crops. The biological preparations Samuel uses help to reduce or replace chemical fungicides and insecticides. The development of biological preparations for use in agriculture is gaining great momentum, not only in Europe but also on other continents.

Figure 4: Installation for the multiplication of microbiological preparations, Brasil. (Source: Author)

Plant diversity and crop rotation

Ensuring high species diversity in crop rotations has many ecological and agronomic benefits. The use of crop rotations with annual crops and the inclusion of intercrops supports a diversity of soil organisms, preventing the dominance of one group of organisms, including pests and pathogens (Mäder et al., 2002). Crop diversity on the soil surface translates directly into greater biodiversity within the soil, which benefits the functioning of the soil ecosystem (Altieri, 1999).

Each plant species has specific nutrient requirements and unique physiological properties. Plants take up different nutrients from the soil, produce diverse root secretions and produce secondary compounds - chemicals that support the plants' natural defence system against pathogens and pests (Hopkins & Gregorich, 2005). The introduction of diverse crop species prevents the one-sided depletion of soil nutrient resources that occurs when monocultures are grown. Repeated cultivation of the same species depletes the same nutrients, leading to reduced soil fertility (Reganold et al., 2016).

An additional benefit of species diversity is an increase in the quantity and quality of crop residues, which affect soil biological and chemical processes to varying degrees. The inclusion of shorter crop rotations and intercropping increases the proportion of diverse plant residues, which provide a source of organic carbon and energy for soil microorganisms, thereby improving soil structure and strengthening soil resistance to degradation (Bastida et al., 2008).

Species diversity in crop rotation is one of the key elements of soil management that contributes to maintaining soil health, fertility and long-term productivity.

Cover crops

Intercrops play a key role in protecting the soil from the negative effects of intensive use and weathering. The permanent vegetative cover of the fields protects the soil from intensive rain, reducing the splash effect that leads to siltation and the formation of an impermeable crust. Thanks to their root network, intercrops effectively prevent water and wind erosion, holding the soil in place (Mäder et al., 2002).

The living roots of intercrops promote soil permeability by allowing water, mineral salts and gases to circulate. Root activity also promotes the formation of a stable soil structure, reducing the negative effects of soil compaction by agricultural machinery (Hopkins & Gregorich, 2005). In addition, the presence of intercrops stimulates soil biological activity, providing micro-organisms with suitable habitat for food and protection.

Intercrops show high resistance to harsh weather conditions, which makes them effective during autumn and winter periods. The rapid growth and competitiveness of these plants allow weed and pest populations to be reduced, further reducing the need to use plant protection products. Many species of intercrops secrete allelopathic substances that reduce the growth of weeds and soil pathogens (Altieri, 1999).

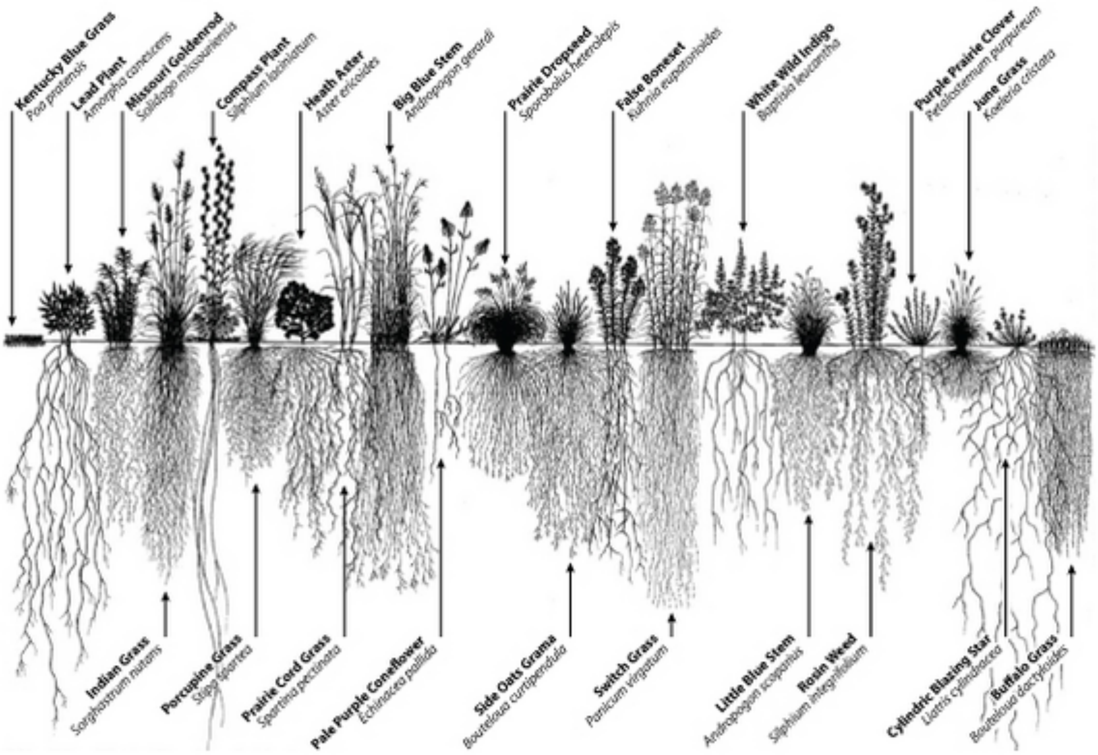

Figure 5: Cover crops, root architecture, (Source: Linsey, 2017)

Economic= and practical benefits

Although intercropping involves additional costs, such as the purchase of seed, herbicides and the labour involved in sowing and destroying them, it brings important benefits in the long term. Fresh plant biomass (leaves, roots, plant residues, root secretions) provides food and protection to soil organisms, contributing to the maintenance of soil structure and nutrient enrichment (Bastida et al., 2008).

Decomposition of organic matter from intercrops leads to the release of mineral nutrients (mineral salts, water, carbon dioxide), which again become available to plants. Thus, intercrops promote a closed nutrient cycle in the soil, increasing soil fertility and resistance to degradation (Reganold et al., 2016).

Advantages of intercropping

- Soil conservation - preventing soil erosion and siltation.
- Preservation of soil structure - maintaining soil stability through biological activity and protection from compaction.
- Resilience and competitiveness - ability to survive harsh conditions, reducing weeds and pests.
- Ease of destruction - ability to eradicate intercrops by mechanical or chemical means.

Intercropping is a key element in regenerative agriculture to promote soil conservation, improve soil structure and maintain fertility (Thomas, 2019).

Case study – Cover crops

Brazil

Regenerative agriculture in the Formoso region, for most farmers, is understood as sustainable farming that can address the challenges of land degradation and climate change. The Formosa region in the state of Goias, is dominated by lateritic soils, known as latosolos, which are typical of tropical areas. These soils are deep-profile, reddish-yellow in colour and poor in nutrients and organic matter, due to intensive weathering and leaching of minerals. These soils are characterised by an acid reaction and low nutrient retention capacity, which poses a challenge for agriculture. They require appropriate management, including liming and fertilisation, and the use of appropriate agrotechnical practices to improve their fertility and agricultural production capacity. An additional very significant challenge is the tropical savannah climate, characterised by a clear division between the rainy and dry seasons. Effective water management and the use of irrigation in regions where annual rainfall ranges from 1,200 mm to 1,500 mm, with the main concentration from October to March, while minimal or no rainfall from April to September, is a key element in achieving high production yields.

It was a very interesting experience for me to visit the farm of Samuel Desconzi, a young farmer running a smallholding where the most profitable crop is oranges. During the farm visit, Samuel shared his experience in the use of intercropping. The main purpose of intercropping on this farm is to protect the topsoil from very high temperatures and to build up organic matter. The main species that are used in intercrop mixtures are biomass-forming and fast-growing grasses with the addition of nitrogen-fixing legumes. Once sufficient biomass has been produced, the catch crops are eliminated using a heavy roller, which lays down the biomass, which then covers and protects the soil from the strong sun and high temperatures. The implementation of

Figure 6: Cover crops in Brasil-protect the top of the soil (Source: Author)

intercropping on many farms in Brazil allows the expansion of narrow crop rotations that mainly consist of one or two main species. The key to successful intercropping in Brazil is the right time of sowing to use the water from the rainy season to their development and to produce biomass when irrigation is not available.

Tillage

One of the main principles of regenerative agriculture, promoted by Gary Zimmer, is an approach to soil tillage that can be summarised by the slogan: ‘cultivate as little as possible and as much as necessary’. According to Gary Zimmer, tillage should be a deliberate action that disturbs the soil in a controlled manner on the one hand and minimises soil degradation on the other.

Soil cultivation should enable the mixing of crop residues, breaking up the layer of compacted subsoil and providing the soil with adequate aeration. Soil, like a living organism, requires access to oxygen. Under oxygen-deficient conditions, the biological activity of the soil decreases and anaerobic areas become a habitat for pathogenic organisms, which can negatively affect yields (Zimmer, 2011). In this context, tillage also has a protective function - it breaks up the soil crust, which restricts air and water flow.

Tillage work should be carried out under optimum soil moisture conditions. Carrying out work on soil that is too wet leads to soil compaction, which requires intensive remedial measures in subsequent years (Mäder et al., 2002).

Odette Menard, a Nuffield from Canada, points out that reduced tillage promotes an increase in the population of earthworms, which are key organisms in creating healthy soil. The population of these organisms can increase by up to 100%, leading to improved soil structure and increased porosity. Odett recalls the words of Charles Darwin: 'The plough is one of the oldest and most important inventions of man. But long before the advent of man, the soil was ploughed and is still ploughed by earthworms'. Healthy soil requires adequate porosity, which allows optimum access to oxygen and supports the life of soil organisms.

Thoughtful soil cultivation supports the decomposition of crop residues. Residues left on the surface oxidise carbon, which ends up in the atmosphere instead of being converted into soil organic matter. The shallow mixing of residues into the soil accelerates their decomposition, warms the soil and nourishes soil organisms. In this way, the soil remains a living ecosystem, capable of sequestering carbon dioxide and providing essential nutrients to plants (Reganold & Wachter, 2016).

Minimising soil compaction

A training course organised by Odette Menard in the province of Quebec outlined the importance of proper tyre pressure to reduce soil compaction. Tyres with a pressure of 6 psi exert a soil pressure of 13 psi, while tyres with a pressure of 17 psi generate a pressure of 24 psi. Reducing the pressure and using additional sets of wheels preserves soil structure and reduces soil degradation.

Figure 7: Effect of tyre pressure on soil compaction, Training for farmers in Canada. (Source: Author)

According to Odette Menard, the more costly management methods, such as subsoiling or drainage, do not solve problems at the full depth of the soil profile. Therefore, Odette proposes the CROP concept, consisting of four principles: cover, roots, oxygen and porosity. Each of these elements interacts with each other and is essential for maintaining soil health.

The soil cover prevents crust formation, improves germination and protects against excessive sunlight. The root system promotes soil porosity, microbial life and glomalin production. Porous soil allows better root access to water and nutrients. Soil compaction reduces water infiltration and oxygen transport, which negatively affects yields and increases production costs.

Odette compares subsoiling to chemotherapy - a practice that should only be used as a last resort. She recommends sowing a cover crop before subsoiling and leaving the field uncultivated for at least a month afterwards, allowing the soil to regenerate optimally.

As part of my visit to the Nexat factory in Germany, I had the opportunity to learn about modern agricultural machinery that supports the development of regenerative agriculture. Nexat's modular design enables operations such as sowing, fertilising or harvesting to be carried out while minimising soil compaction. Moving the machines along fixed tramlines promotes soil regeneration, protects soil structure and encourages the development of soil microorganisms.

Figure 8: Nexat technology (Source: Einboeck, 2024)

Thoughtful soil cultivation is a key element of regenerative agriculture that supports soil fertility and biological activity. The use of advanced technologies and a conscious approach to soil cultivation not only maintains the health of the soil, but also increases the efficiency of agricultural production in a sustainable manner.

Feed the soil

When we think of soil, many of us see it merely as a creation - a lifeless, inert, inorganic dust that provides a surface for plants and animals to live on. However, we sometimes forget about the abundance of life that inhabits the soil. In fact, soil life is extremely complex and diverse: one teaspoon of healthy soil can harbour up to 15 000 species of bacteria, not to mention other forms of life. It can also house more individual microorganisms than there are humans on Earth.

The soil food web is complex and driven by organic matter, such as decaying plants, animals and microbes, as well as nutrients released by living plant roots. Organic matter is digested by bacteria, fungi and other microorganisms, which in turn become food for earthworms, insects and spiders. Finally, larger animals such as mice and moles inhabit the soil and live by feeding on smaller organisms.

All these creatures are essential for a healthy soil structure. Even small disruptions to this network can trigger a chain of reactions leading to soil ecosystem dysfunction (Lehman, 2015).

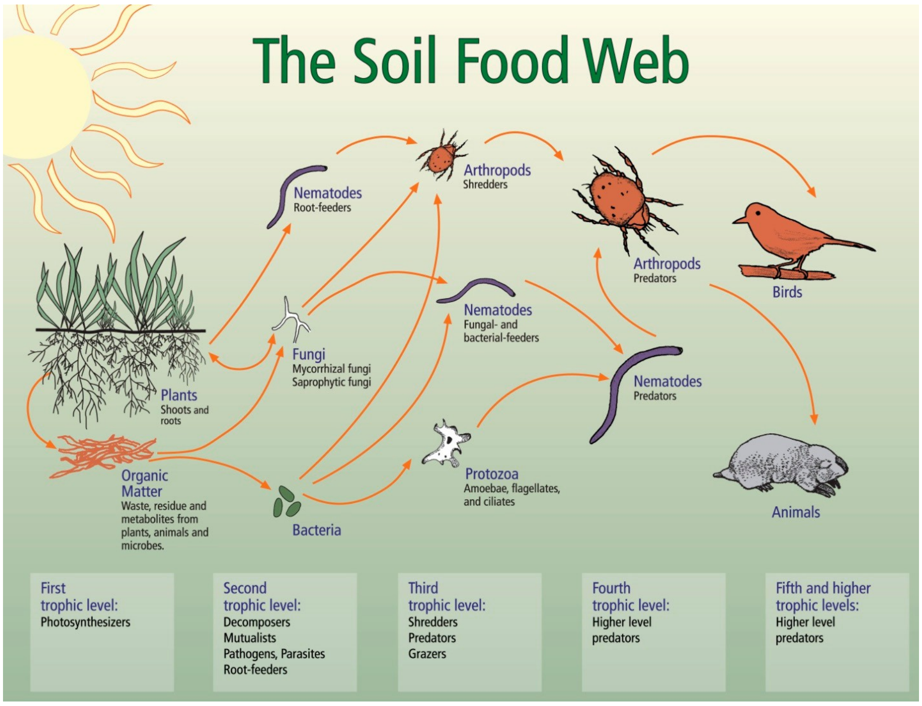

Figure 9: The soil food web. (Source: Soil Biology Primer, 2000)

Compost production

The Johnson-Su method is a compost making technique that is gaining popularity among farms, one example being G's Fresh in the UK. It is a method that places great emphasis on the quality and balanced microbial composition of the compost, which has a positive impact on soil health and yields.

Key principles of the Johnson-Su method

The Johnson-Su method involves a slow and natural process of biomass fermentation under conditions that provide adequate air flow and moisture. Unlike traditional composting methods, this technique does not involve turning the pile over. The process typically takes 9-12 months to produce compost with high microbial activity.

The mature compost can be used as an extract, mixed as a slurry to coat seeds to be planted on large farms, or applied directly as a soil amendment.

Compost from Johnson-Su composting bioreactors improves seed germination rates when used to coat seeds, improves soil water infiltration and water retention, helping to increase soil carbon content, and increases plant health, plant growth rates and crop production (Johnson, 2017).

Figure 10: Johnson-Su compost production and application at G's-fresh farm. (Source: Author)

Molasses

Gary Zimmer, whom I visited in Wisconsin, highlights the importance of molasses as an ingredient to support soil health and crop efficiency. Molasses, a by-product of sugar cane or sugar beet processing, plays a key role in improving soil biology, enhancing microbial activity and supporting sustainable agricultural practices.

Figure 11: Meinke Ostremann and Gary Zimmer pioneer of organic farming, Wisconsin, USA. (Source: Author)

Main uses of molasses in regenerative farming

1. Stimulation of soil micro-organisms.

Molasses provides easily digestible carbohydrates that provide a source of energy for soil microorganisms. Gary Zimmer uses it to increase the population of beneficial micro-organisms, such as bacteria and fungi, which promote the mineralisation of organic matter, the release of nutrients and the improvement of soil structure.

2. Supporting composting processes

In regeneration practices, molasses acts as an additive to accelerate the fermentation process in the compost. Thanks to its properties, micro-organisms decompose organic residues more quickly, resulting in a compost richer in micro- and macro-elements.

3. Improving the assimilation of nutrients

Many farmers use molasses in foliar fertilisation, combining it with micronutrients to increase their bioavailability to plants.

4. Controlling diseases and pests in the soil

By supporting the biological activity of the soil, molasses reduces the development of soil pathogens and unfavourable organisms, enhancing the soil's natural protective processes.

Application of molasses

Molasses can be applied in various forms:

- Dissolved in water and used to water the soil or plants.
- As an additive to compost or fermentation slurry.
- As an ingredient in fermented biological preparations.

The recommended dose is usually 5-15 litres of molasses per 200 litres of water, but proportions may vary depending on the purpose of the application. It is important to use molasses in moderate quantities to avoid saturating the soil with sugars, which could upset the microbial balance.

Agroforestry-case study

An example of an innovative approach to regenerative agriculture is the farm of Jan Grobe-Kleimann in North Rhine-Westphalia. Since 2020, regenerative agriculture has been a key part of this farm's management, with a focus on building humus and developing soil life. To achieve these goals, the soil is kept green all year round, if conditions allow, and soil cultivation is kept to a minimum. In addition, a wide range of intercrops are introduced and soil fertilisation is carried out in a sustainable manner, reducing the use of mineral fertilisers and plant protection products.

One of the key elements of Jan Grobe-Kleimann's farm is the implementation of an agro-forestry system, which combines agricultural intensification with ecosystem regeneration. This system integrates annual crops, such as cereals, maize or grassland, with woody plants. In

November 2022, the first agroforestry system was established in a field at the entrance to the farm, including the planting of 450 apple trees.

The main objectives and benefits of agroforestry on the farm include:

1. **Erosion reduction:** Trees provide natural protection from the wind, reducing the risk of wind erosion. In summer, they reduce the rate of water evaporation, which reduces heat stress on crops.
2. **Symbiotic effects:** The total yield of apples and cereals or maize is higher than if they were grown separately.
3. **Healthy ecosystem:** Tree belts contribute to biodiversity and the number of species in an area. Wildflowers in tree belts favour beneficial insects, making it possible to reduce the use of plant protection products. These phenomena are monitored in cooperation with the University of Münster as part of a research project.
4. **Improved air and soil quality:** Carbon sequestration in the soil is significantly higher than with traditional arable land use. At the same time, the humus content of the soil increases.
5. **Soil richness:** Tree roots reach deeper into the soil, extracting nutrients not available to annual plants. This reduces nutrient leaching and improves soil structure.

The implementation of an agroforestry system on Jan Grobe-Kleimann's farm shows the great potential of this approach in the context of integrated agricultural production and environmental protection. This example can serve as an inspiration for other farms seeking to integrate regenerative practices into their daily operations.

Another farm with a strong commitment to regenerative farming practices is that of Alexander Schierholz-Prilop. Alexander emphasised that his aim is to farm beyond sustainability. His mission is not just to maintain the current state, but to continuously improve the health of the ecosystem. 'We want to protect the land, build humus and restore natural cycles,' he said.

He follows a few key principles on his farm:

- **No-till system**: All fields on the farm are sown using no-till technology, which reduces erosion and improves soil quality.
- **Diversified crop rotation**: The crop rotation includes cereals, winter rape, maize, grassland and legumes such as peas and broad beans.
- **Permanent soil nutrition**: It is important to maintain living roots in the soil throughout the year. To this end, rich intercrop mixtures are sown to provide food for soil organisms.
- **Integration of animals**: In natural ecosystems, animals play a key role. The farm's herd of cattle is moved to a fresh piece of pasture each day, which promotes soil regeneration.

- **Agroforestry**: The introduction of several thousand poplar trees provides shade and protection for the chickens, while in the fields it slows down the wind and improves the microclimate.

Alexander Schierholz-Prilop's farm is an example of a comprehensive approach to regenerative agriculture that combines modern techniques with respect for natural ecological processes.

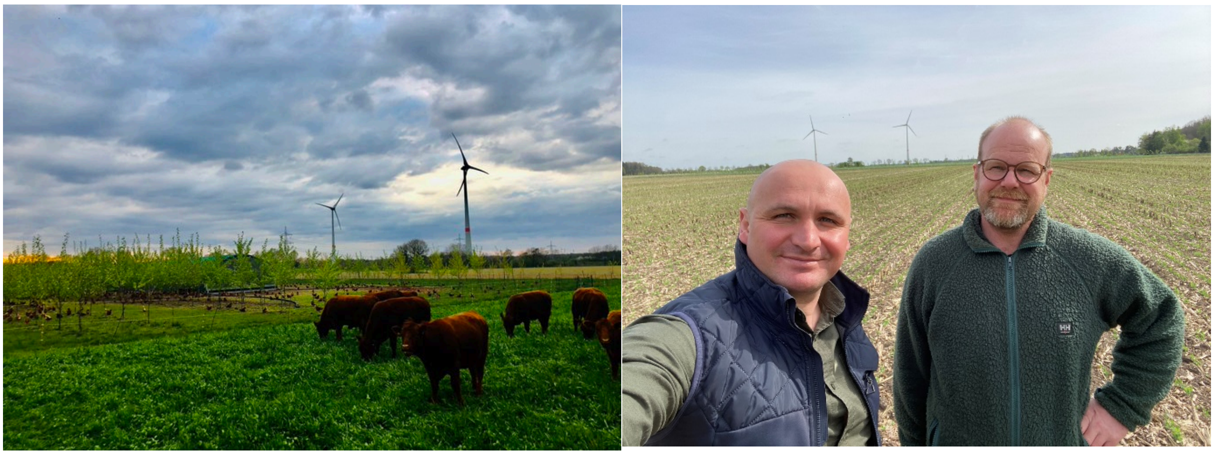

Figure 12: Agroforestry and Alexander Schierholz-Prilop, Germany. (Source: Author)

Stephen Briggs-Nsch, is another example of a farmer in the UK who has successfully implemented the principles of regenerative agriculture. His farm in Cambridgeshire combines traditional farming practices with modern agroforestry techniques, which not only increases agricultural productivity but also supports biodiversity and soil restoration.

Figure 13: Agroforestry and Stephen Briggs Nsch, UK, (Source: Author)

Stephen explained that if you want to increase agricultural production, consider a space 2 metres above and 1 metre below the surface.

“If you put a farmer and a forester in a field together they never make eye contact. The farmer look at the ground and the forester look up at the trees: the only person looking forward is the agro-forester”

More than 4,500 including around 16 different varieties of apple trees have been planted on Stephen Briggs' farm in a strip system, which has significantly increased biodiversity. These trees create microhabitats that attract a variety of animals, insects and birds that play key roles in the functioning of ecosystems. The roots of the trees enrich the soil structure and promote the growth of micro-organisms, which contributes to soil fertility and carbon storage capacity.

The agroforestry system also supports the presence of natural pollinators, such as bees and bumblebees, which benefit from the abundance of flowering plants within the farm. A greater diversity of pollinators has a positive impact on the yield of both trees and agricultural crops, which increases ecosystem stability and productivity.

The agroforestry system used by Stephen Briggs helps to reduce soil erosion, reduce nutrient loss and increase biological activity in the soil. Soil organisms such as bacteria, fungi and earthworms find optimal conditions for growth in this system. Their presence improves soil structure and supports natural processes such as mineralisation and carbon sequestration.

Stephen Briggs' farm is a model example of how regenerative agriculture and agroforestry can transform intensive agricultural landscapes into a mosaic of ecosystems that support biodiversity. His farm model can serve as an inspiration for other farmers seeking sustainable solutions for the future of agriculture.

Conclusion and recommendations

As the first Polish Nuffield International Fellow, I had the opportunity to research and analyse the global experience of regenerative agriculture, focusing on practices that can significantly improve soil health and support sustainable agricultural development in Poland. The conclusions in the report are based on visits to farms around the world and interviews with farmers, scientists and experts.

The most important practices I recommend implementing to improve soil health are:

1. **Minimise tillage** - reduce mechanical intervention in the soil to maintain soil structure, increase biological activity and reduce erosion.
2. **Use of intercropping** - intercropping protects the soil from erosion, increases organic matter and reduces weed growth while promoting microbial activity.
3. **Diversifying croprotations** - species diversity in crops promotes soil health, increases soil fertility and prevents depletion.
4. **Regular soil analysis** - testing identifies nutrient deficiencies and adjusts fertilisation, including balancing key minerals such as calcium and magnesium.
5. **Enriching the soil with organic matter** - the use of compost, bio-fertilisers and organic fertilisers promotes soil fertility, improves water storage capacity and reduces degradation.
6. **Soil conservation** - ensuring continuous soil cover, reducing the use of pesticides and chemical fertilisers.
7. **Animal integration** - rotational grazing and proper grazing management promote nutrient cycling and improve soil structure.

Applying these principles not only supports soil health and increases yields, but also makes crops more stable in the face of a changing climate and drought challenges. Improving soil structure and increasing water-holding capacity make cropping systems more resilient to extreme weather conditions.

Transitioning to a regenerative farming system

The transformation of a farm to regenerative agriculture should be implemented in a deliberate and gradual manner:

1. **Education and planning**: Gain knowledge of the principles of regenerative agriculture and define long-term goals for the transformation.
2. **Farm condition assessment**: Soil analysis, identification of available resources and prioritisation of actions.
3. **Implementing change**: Starting with simple practices such as introducing intercropping, reducing soil tillage intensity and diversifying crop rotations.
4. **Monitoring progress**: Regular soil testing, observing the effects of changes and adjusting strategies.
5. **Long-term commitment**: Establish new practices and develop partnerships with other farmers.

Transitioning to regenerative agriculture takes time, patience and consistency, but has benefits in terms of improved soil health, increased yields and greater stability of agricultural production in the face of a changing climate. I believe that implementing these practices will help farmers meet the challenges of modern agriculture and ensure a better future for our farms and environment, as well as increase yields while reducing production costs.

Bibliography

Albrecht, W. A. (1975). *The Albrecht Papers, Vol. I-VII*. Acres, USA.

Allison, F. E. (1973). *Soil organic matter and its role in crop production*. Elsevier Scientific Publishing Company.

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment*, 74(1-3), 19–31.

Bastida, F., Zsolnay, A., Hernández, T., & García, C. (2008). Microbial activity in soil under arid conditions: The importance of organic amendments. *Applied Soil Ecology*, 38(1), 11–20.

Carvalho, S. J. P., & Christoffoleti, P. J. (2008). Glyphosate Resistance in Weeds: Implications for Brazilian Agriculture. *Planta Daninha*, 26(3), 585-590.

Darwin, C. (1881). *The Formation of Vegetable Mould Through the Action of Worms with Observations on Their Habits*. John Murray.

Einboeck, (2024), "NEXAT can now do mechanical weeding", Einbock website, https://www.einboeck.at/en/newsroom/news/nexat-can-now-do-mechanical-weeding

Górka, J. (2016). *Chemia gleby*. Warszawa: Wydawnictwo Naukowe PWN.

Heap, I. (2023). The International Survey of Herbicide Resistant Weeds. Retrieved from www.weedscience.org.

Hopkins, D. W., & Gregorich, E. G. (2005). Carbon as an energy source for soil organisms. In *Soil Microbiology, Ecology, and Biochemistry* (pp. 81–100). Academic Press.

Johnson, D., DeSimio P., (2017) Best Management Practices: Johnson-su composting bioreactors.

Kinsey, N. (2013). *Hands-on Agronomy*. Acres USA. Texas, USA.

Lehman, R. M., Cambardella, C. A., Stott, D. E., & Acosta-Martínez, V. (2015). Understanding and enhancing soil biological health: The solution for reversing soil degradation. *Sustainability*, 7(1), 988–1027.

Linsey, J, (2017), Deep rooting cover crops??? Blog, Permies Website, https://permies.com/t/55328/Deep-rooting-cover-crops

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science*, 296(5573), 1694–1697.

Magdoff, F., Harold M. van Es, (2009). *Building Soils for Better Crops*. Beltsville: Sustainable Agriculture Network.

Menard, O. (2023). *Soil Conservation in Practice: Reducing Tillage for Improved Soil Health*. Nuffield Scholarship Report.

Mortensen, D. A., Egan, J. F., Maxwell, B. D., Ryan, M. R., & Smith, R. G. (2012). Navigating a Critical Juncture for Sustainable Weed Management. *BioScience*, 62(1), 75–84.

Nichols, K. A. (2018). Soil health and sustainable agriculture. *Soil Science Society of America Journal*, 82(2), 10–18.

Owen, M. D. K. (2008). Weed Species Shifts in Glyphosate-Resistant Crops. *Pest Management Science*, 64(4), 377–387.

Powles, S. B., & Yu, Q. (2010). Evolution in Action: Plants Resistant to Herbicides. *Annual Review of Plant Biology*, 61, 317–347.

Reganold, J. P., & Wachter, J. M. (2016). Organic Agriculture in the Twenty-First Century. *Nature Plants*, 2(2), 15221.

Thomas, F., & Archambeaud, M. (2019). *Międzyplony w praktyce*. Oikos, Warszawa.

Zimmer, G. F., & Zimmer-Durand, L. (2011). *Advancing Biological Farming*. Acres USA