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Sustainable Agricultural Practices for Enhancing Soil Quality

Bachelor's Thesis

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Organic farming AGRIBE

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Declaration

I hereby declare that I have authored this bachelor’s thesis carrying the name „Sustainable Agricultural Practices for Enhancing Soil Quality“ independently under the guidance of my supervisor. Furthermore, I confirm that I have used only professional literature and other information sources that have been indicated in the thesis and listed in the bibliography at the end of the thesis. As the author of the bachelor’s thesis, I futher state that I have not infringed the copyrights of third parties in connection with its creation.

In Prague on 25.4.2025 ____________________________

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Abstract

This thesis provides a comprehensive literature review of sustainable agroecological practices and their role in enhancing soil quality. It examines chemical, physical, and biological indicators including soil organic carbon, aggregate stability, and soil biodiversity. The review demonstrates that soil organic carbon content, aggregate structure, and microbial activity are significantly improved by practices such as organic amendments, conservation tillage, and cover cropping. Specifically, the application of compost, digestate, and vermicompost enhances microbial diversity and enzyme activity more effectively than mineral fertilizers alone. The integration of legumes and diverse cover crop mixtures increases nitrogen availability and soil resilience.

European case studies, including those from the Czech Republic, highlight that organic and conservation farming systems can be economically viable and environmentally beneficial when appropriately managed. The Czech Republic has experienced significant growth in organic farming, with a high proportion of profitable farms. Conservation agriculture measures – such as reduced tillage and green manures – have been linked to improved soil organic carbon levels, enhanced biological activity, and more efficient nitrogen cycling.

Despite clear environmental benefits, adoption of these practices faces persistent barriers including economic constraints, limited policy support, technical knowledge gaps, and social resistance. However, the findings show that sustainable soil management is achievable across various farm scales and systems when practices are tailored to local contexts and supported by education and long-term policy incentives.

Keywords: Sustainable agriculture; soil health; agroecological practices; soil conservation

Content

1 Introduction

Soil quality stands at the cornerstone of sustainable agriculture and global food security. As Franklin Delano Roosevelt (1937) stated, "A nation that destroys its soils destroys itself" – a statement that remains critically relevant today. In an era of increasing environmental challenges and growing food demand, the maintenance and enhancement of soil quality have become paramount concerns in agricultural science and practice.

Soil, fundamentally composed of water, air, organic matter, and minerals, represents a complex and dynamic ecosystem that supports all terrestrial life. These components interact through biochemical processes to determine soil physical and chemical properties, directly affecting crop yields and ecosystem health. Despite its crucial role, soil has been historically undervalued, leading to widespread degradation through intensive agricultural practices.

The emergence of agroecological practices represents a promising approach to addressing these challenges. These practices integrate traditional agricultural knowledge with modern scientific understanding, aiming to enhance soil quality while maintaining productive agricultural systems. Recent research across Europe has demonstrated the potential of agroecological approaches in improving soil quality parameters and related ecosystem services.

The relationship between agroecological practices and soil quality continues to be a focus of active research, utilizing both qualitative field observations and quantitative analytical methods. Understanding these relationships is crucial for developing sustainable agricultural systems that can meet current production needs while preserving soil resources for future generations.

2 Objectives

This thesis presents a comprehensive literature review on soil properties and agroecological practices. The specific objectives were to:

- Investigate the physical, chemical, and biological properties of soil and their impact on agricultural productivity and ecosystem health.
- Evaluate key agroecological practices and their effects on soil health, including an analysis of tillage methods, fertilization strategies, and cover cropping systems, considering their benefits and implementation challenges.
- Provide examples of various soil management approaches and their outcomes based on European case studies.
- Offer insights into how agroecological practices can be effectively implemented to enhance soil quality in diverse agricultural contexts.

3 Sustainable Soil Management

3.1 Soil Quality Indicators

Soil quality refers to how well soil can perform essential functions, such as supporting plant growth and contributing to environmental health. It involves analyzing various soil characteristics and understanding how they interact. A soil quality indicator is a specific measurement that reflects the impact of farming practices on soil and the environment.

Scientists have found that looking at just one aspect of soil isn't enough to understand its overall health. Instead, they use what's called a minimum dataset (MDS) – a collection of important physical, chemical, and biological measurements that together give a complete picture of soil health (Seybold et al. 1997; Rezaei et al. 2006). However there is no universal „one-size-fits-all“ MDS. The specific measurements chosen depend on local conditions, such as climate and farming practices (Govaerts et al. 2006; Yao et al. 2013).

One of the biggest challenges in studying soil quality is that soil changes very slowly. This makes it hard to see how farming practices or environmental problems affect the soil right away. By the time we notice serious damage, it might be too late to fix it. For example, in some parts of the Mediterranean region, so much soil has been lost to erosion that it can't be restored (Zuazo & Pleguezuelo 2008). This shows why it's so important to regularly check soil health at both local and regional levels (Grunwald et al. 2015).

When studying soil health, scientists look at three main types of properties: chemical, physical, and biological. Chemical properties are the most commonly studied because they directly affect plant growth and are relatively easy to measure (Bünemann et al. 2018; Cardoso et al. 2013). These include organic carbon, pH, and nutrient levels (Bünemann et al. 2018). Physical properties, such as soil structure, bulk density, and water retention, are important indicators of soil health because they influence soil stability, water movement, and aeration (Cardoso et al. 2013). Biological properties play a key role in soil health, especially through ecosystem engineers like earthworms, ants, and plant roots. These organisms shape the soil, create habitats for other creatures, and influence soil processes through their activities (Lavelle et al. 2016).

3.1.1 Chemical Indicators

Soil Organic Matter (SOM) and Soil Organic Carbon (SOC)

Soil organic matter serves as a key indicator of soil health and fertility (Maurya et al. 2020). According to Lal (2016), soil organic matter is the organic fraction of soil composed of decomposed plant and animal materials, as well as microbial organisms. Soil organic carbon represents the carbon associated with this organic matter. This carbon must be continuously replenished, as without regular additions of organic matter, soil life would eventually disappear when microorganisms consume the existing SOC stock (Meurer et al. 2020). As a significant terrestrial carbon reservoir, SOC improves several essential soil properties including water retention (Lal 2020), nutrient exchange capacity (Ramos et al. 2018), and nutrient availability (Lal 2016). It is important to note that measuring SOC stocks reliably requires extensive data collection over time, which is why properly designed long-term field experiments are essential for understanding any effects (Lorenz et al. 2019).

Humic Substances (HS)

Humic substances represent the final stage of organic matter decomposition (Mosa et al. 2020) and can last in soil for decades to centuries (Brady & Weil 2008). They are divided into three groups based on their stability and solubility: humin (most stable), humic acid (moderately stable), and fulvic acid (least stable) (Stevenson 1994). The ratio of Humic acids to Fulvic acids (HA/FA) is presented as an important indicator of SOC quality and degree of humification. Higher ratios typically show more decomposed, stabilized organic matter – indicating advanced humification processes (Dudek et al. 2022). These substances play crucial roles in promoting root growth (Canellas & Olivares 2014), making nutrients like iron and zinc more available (Chen et al. 2004) and improving soil structure and aggregate stability (Mbagwu & Piccolo 1989).

Cation Exchange Capacity (CEC)

CEC is widely recognized as a key chemical property that influences soil fertility and nutrient availability (Cardoso et al. 2013). It functions as a soil's nutrient reservoir – soils with higher CEC can retain and exchange more essential nutrients, wicht enhancing plant growth (Aprile & Lorandi 2012). However, CEC values can vary significantly depending on the measurement technique used (Chapman 1965; Aprile & Lorandi 2012). Assessing CEC is essential for optimizing nutrient management, as it can help reduce fertilizer costs by improving nutrient retention. Soils with high CEC hold nutrients longer, decreasing the need for frequent fertilization, whereas low-CEC soils, such as sandy or highly weathered ones, struggle to retain nutrients, leading to increased fertilizer requirements and greater nutrient loss through leaching (Aprile & Lorandi 2012)

pH

Soil pH acts as a "master variable" that affects many soil processes (Brady & Weil 2008; Minasny et al. 2016). The majority of crops grow in soils with pH between 6 and 7.5. pH levels are influenced by several key factors including CO_2 from organic matter decomposition and root respiration, aluminum reactions with water, nitrification, sulfur compounds, and acid rain. pH controls the solubility of metals (Al, Fe, Mn, Cu, Zn) and nutrients like phosphorus, while also affecting soil bacteria, which are typically sensitive to low pH except for acidophil species (USDA NRCS 2015). This two-way relationship – where pH affects soil processes and soil processes affect pH – makes pH a key indicator of soil health (Brady & Weil 2008; Minasny et al. 2016).

Micro and Macronutrients Concentration

The assessment of soil nutrients has become increasingly important with the development of better laboratory techniques (Fageria & Baligar 2005). Key nutrients like phosphorus, potassium, calcium, and magnesium are essential for plant growth (O'Neill et al. 2021). Their availability is affected by other soil properties such as organic matter content, pH, and moisture levels (Fernández & Hoeft 2009). Regular nutrient testing helps maintain soil fertility and prevent environmental problems from over-fertilization (Zhang et al. 2018).

Total Nitrogen (N) Content

Nitrogen is highly dynamic in soil systems and difficult to maintain at stable levels (Chen et al. 2014). While total nitrogen content provides important information about current soil status, it doesn't tell much about long-term soil health (Bonde et al. 1988). Plants need different amounts of nitrogen throughout their growth cycle, requiring careful management of this nutrient (Sainz-Rozas et al. 2004; Padilla et al. 2020).

3.1.2 Physical Indicators

Soil Aggregate Stability (SAS)

SAS refers to how well soil particles (sand, silt, clay) and organic matter stick together to form aggregates. Strong aggregates help maintain soil structure, improve water retention, and prevent erosion. Soil aggregate stability is the ability of soil aggregates to remain intact when exposed to stresses (Amézketa 1999). In soils with over 15% clay (particle size <0.002 mm), particles naturally form aggregates, which support soil structure. This process occurs through drying and swelling cycles, as well as biological activities (Horn et al. 1994). According to Tisdall and Oades (1982), organic binding agents are organic materials that help hold soil particles together into aggregates. They classify these into three main types: transient (polysaccharides), temporary (roots and fungi), and persistent (humic materials). SAS can serve as one of several indicators of soil quality and influences soil sustainability and crop production (Amézketa 1999), water availability (Zhao et al. 2007), soil erosion resistance (Barthès & Roose 2002), and aeration (Rathore et al. 1982). However, heavy machinery can reduce SAS, making soil less stable and more prone to erosion (Schlüter et al. 2018). The term "SAS" is sometimes used inconsistently, with some researchers referring to only large aggregates (Amézketa 1999). While SAS is a valuable soil quality indicator, it should not be used alone but rather alongside other soil physical quality measures (Pulido Moncada et al. 2015).

Bulk Density (BD)

BD measures how compact soil is, expressed in grams per cubic centimeter (g/cm^3). Higher BD means soil is denser, which can limit plant growth by reducing root development and affecting soil water movement. BD is a quick way to assess soil compaction. However, BD alone is not sufficient as an indicator since it does not capture important aspects of soil structure (Rabot et al. 2018). Also to mention that it increases with heavy machinery use (Schlüter et al. 2018) and poor soil management (Valpassos et al. 2001). Bulk density (BD) directly influences soil aggregate stability (SAS) through negative correlations (García-Orenes et al. 2005), soil water retention (SWR) by serving as a key predictive parameter (Gupta & Larson 1979), and biological properties (Ungaro et al. 2022).

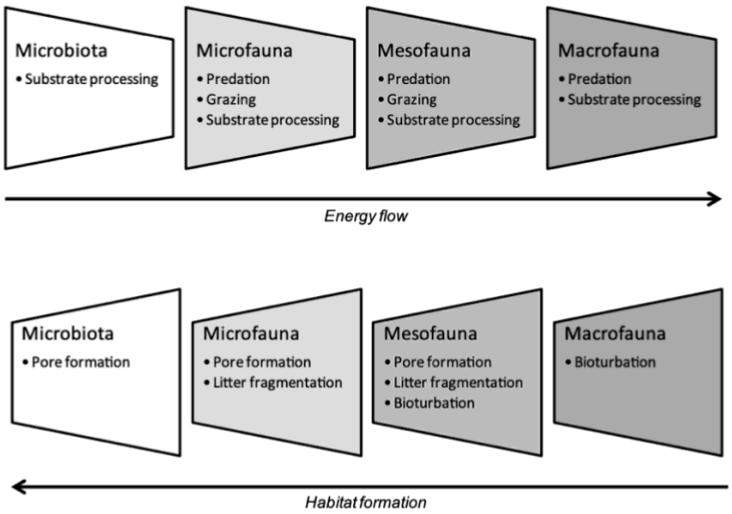
Soil Water Retention (SWR)

Soil water retention (SWR) is the soil's ability to hold water, which is crucial for plant growth and drought resistance. According to Razzaghi et al. (2020), soil water retention depends on various factors including soil texture, clay content, aggregation, pore size, and organic matter content. Farmers can improve SWR in two ways: by adding water-attracting materials like biochar (Razzaghi et al. 2020) or compost (Gould 2015), and by using conservation farming practices such as minimal tilling and cover crops (Scott et al. 1986; Sullivan 2002; Lal 2020).

3.1.3 Biological Indicators

Scientists have found that there is a strong, positive linear relationship between ecosystem multifunctionality and soil biodiversity, showing that ecosystems function better when soil contains a greater variety of living organisms (higher biodiversity), including bacteria, fungi, and other soil biota. The composition of soil communities supports essential processes like plant diversity, decomposition, and nutrient cycling (Wagg et al. 2014). Many of these diverse organisms live hidden in the soil where we cannot observe them, and researchers still don't fully understand how changes in the types and numbers of these soil organisms affect ecosystem functioning (Wagg et al. 2014; Delgado-Baquerizo et al. 2018;).

Most land-based biodiversity hides in soils, where organisms drive critical services such as climate regulation and soil fertility. Soil organisms are classified by both their size (as macro-, meso-, micro-fauna, and microbiota) and their position in the food web or trophic level (Figure 1), providing different perspectives for analysis. These soil biota shape soil structure, distribute organic matter, and serve as indicators of soil quality in monitoring programs (Nielsen et al. 2002; Briones 2014). Unlike chemical or physical measurements, biological indicators reveal how soil functions and its community structure, though they're harder to study and lack standardized methods. The most effective indicators focus on organisms that control nutrient cycles or connect ecosystem components (Schloter et al. 2018). Research shows that only 0.1–2% of soil microorganisms are active, currently breaking down nutrients and supporting soil processes. Another 10–60% are potentially active and can start working quickly when nutrients are available, though this depends on the soil and measurement method, which makes accurate sampling and analysis quite tricky (Blagodatskaya & Kuzyakov 2013).



Fifure 1. Tropic and engineering interactions among soil organism (Briones 2014)

Macrofauna: Earthworms

Earthworms, the largest animal biomass in soil (0.1–12 g dry weight/m²), boost fertility by creating tunnels and improving porosity (Jeffery et al. 2010). As "biological engineers," they serve as easy-to-study bioindicators of soil quality because they are simple to collect and identify (Paoletti 1999). They fall into three groups: epigeics (surface-dwellers), anecics (topsoil burrowers), and endogeics (subsoil dwellers) (Giffard et al. 2022). These groups influence plant growth by creating pores and modifying soil structure for roots (Wurst et al. 2018). Earthworms increase soil porosity, microbial biomass, enzyme activity, and N content (Fusaro et al. 2018), as well as crop yield and aboveground biomass (Van Groenigen et al. 2014). Their sensitivity to environmental stresses makes them indicators of soil quality (Yan et al. 2012). Soil management affects their ecology (Giffard et al. 2022).

Mesofauna: Microarthropods

Microarthropods are small creatures that live in the soil and play many important roles in keeping soil healthy. According to Lavelle et al. (2006) and Brussaard et al. (2007), they help distribute organic matter, mix soil layers through their movement (bioturbation), break down plant material into smaller pieces, and create soil structure through their burrowing, casting, and nesting activities.

These tiny soil animals are grouped into three categories based on where they live in the soil: epi-edaphic (living on the surface), hemi-edaphic (living in the middle layers), and eu-edaphic (living deep in the soil). Each group has different roles in breaking down organic matter (Gagnarli et al. 2015).

Springtails (Collembola) and certain mites (especially Oribatida) are the most studied microarthropods in soil ecosystems. The Oribatida group includes more than 10,000 species worldwide and is especially important for decomposition in forests and grasslands as mentioned by Culliney (2013). Gagnarli et al. (2015) found they are also very common in vineyards. These organisms help decomposition directly by eating organic matter and indirectly by consuming fungi and bacteria that break down plant material.

Most microarthropods live in the top 10 centimeters of soil. The amount of microarthropods in soil reflects how much organic matter is available, and the types present can indicate how quickly nutrients are being recycled. Because these creatures don't move very far, they effectively show the effects of stress on soil. Their sensitivity to environmental problems like pollution makes them useful indicators of soil health (Coleman et al. 2004; Gagnarli et al. 2015)

Scientists have developed several indices (like QBS-ar, QBS-c, IBSQ, QBS-BF) based on microarthropod abundance, presence, and diversity to assess soil quality (Parisi et al. 2005). The richness and diversity of these small animals in soil can indicate how mature and stable the soil ecosystem is.

Nematodes (Microfauna)

Nematodes are among the most abundant multicellular animals on Earth, occupying various feeding positions in soil food webs. Many feed on bacteria and fungi, regulating decomposition and nitrogen cycling. Neher (2001) recommends using nematode communities as soil health indicators due to their connection with key soil processes. Song et al. (2015) found that nitrogen fertilization decreases nematode diversity but increases their numbers. Scientists use tools like the Maturity Index (Bongers 1990) and Ferris indices to evaluate soil health through nematode populations. Nematodes provide ecosystem services through nutrient cycling and pest control by eating other organism. While farming affects nematode communities, they're generally less sensitive to practices like tillage than larger soil animals.

Microorganisms

Microorganisms play key roles in carbon and nutrient cycling, representing a fundamental link in biogeochemical cycles. They impact plant, animal, and human health through various functions. In the rhizosphere, bacteria such as Rhizobium support plant growth by colonizing roots, reducing pathogens, and providing nutrients (Hayat et al. 2010). Free-living bacteria like Azospirillum are essential for nitrogen fixation and plant hormone biosynthesis (Steenhoudt et al. 2000). Bacterial activity decreases at low pH levels, affecting organic matter mineralization, soil structure, and nitrogen cycling (Geisseler et al. 2014).

Moving to fungi, these organisms decompose organic matter, especially complex compounds like lignin and cellulose, and recycle nutrients. Giffard et al. (2022) note that their filamentous structure contributes to aggregate formation and soil stability. Many fungi act as endophytes or root associates, with some Trichoderma species activating plant defenses against pathogens. Particularly important are arbuscular mycorrhizal fungi (AMF) provide nutrients to plants, especially in low-input systems. They also increase plant tolerance to various stresses including water stress, soil salinity, iron chlorosis, and heavy metal toxicity, while protecting against root diseases.

Lastly, soil viruses affect other soil microbiota, biochemical processes, nutrient cycling, and greenhouse gas emissions. However, Emerson (2019) points out that their impact on crop health, yield, and production quality has not been fully discovered yet.

4 Agroecological practices

Agroecology studies food systems by integrating ecological, economic, and social dimensions (Francis et al. 2003). According to Gliessman (1998), agroecology's origins can be traced back to the early 1900s, when ecologists and agronomists discovered shared research interests. At that time, researchers in crop ecology were studying crop distribution patterns and their climate adaptation. This convergence of ecological and agricultural research led some scientists to propose the term "agroecology."

It's important to note that agroekology has dual meanings in current literature. Originally referring to the scientific discipline studying agricultural ecosystems, the term has evolved to also describe a set of sustainable agricultural practices and approaches. In this thesis, while acknowledging agroecology as a scientific discipline that objectively studies different farming systems, we focus on sustainable agroecological practices.

Sustainable agroecological practices are proposed as a model for agricultural production and food system organization (Matthews 2022). Unlike conventional agriculture, which prioritizes production increases through larger farm sizes, specialized output, and intensive technology, these practices aim to optimize farm resources and reduce external costs rather than maximize yields (van der Ploeg et al. 2019). They encompass techniques such as reduced tillage, diverse rotations, appropriate fertilization, organic amendments, and cover cropping, which work synergistically to enhance soil health and farm sustainability, rather than depending on any single method (Khangura et al. 2023). While these practices overlap with regenerative agriculture – a specific system focused on soil regeneration and carbon sequestration – they are broadly applicable within agroecological frameworks.

Numerous studies have documented the benefits of sustainable agricultural practices, including organic farming, showing reduced environmental impact and enhanced soil quality compared to conventional systems (Marinari et al. 2006). Agroecological practices are promoted to conserve soil and help preserve soil quality, fertility, and health. Alternative practices like regenerative and biodynamic farming improve soil health and microbial biomass more effectively than conventional methods (Fließbach et al. 2007; Montgomery et al. 2022).

Studies have found that while agroecological farms typically require more labor, they can achieve income levels similar to conventional farms by reducing external input costs (van der Ploeg et al. 2019). While organic yields are typically lower than conventional yields (averaging 25% lower), the yield gap varies significantly depending on growing conditions and management practices (Seufert 2012). Under optimal conditions – such as with rain-fed legumes and perennials on certain soil types – organic systems can come close to matching conventional yields. However, yields are just one of many factors to consider when comparing farming systems (Seufert 2012).

Phalan et al. (2016) argue that increasing agricultural productivity on existing farmland could reduce the need to convert natural habitats into agricultural land. However, they emphasize that yield improvements alone are insufficient; there need to be specific rules and rewards to ensure that when farmers grow more food on their existing land, natural habitats are actually protected.

Most successful agroecology cases involve smallholder farming, which occupies 30% of global agricultural land (Tittonell et al. 2020). Large-scale agroecology requires research, technology, and policy support (Tittonell 2020). Knowledge gaps persist regarding practical strategies for large-scale transitions. Scaling agroecology in large farms could yield social (jobs, education, business), natural (biodiversity, soil, water quality), financial (long-term profits), and emotional (inspiration, well-being) benefits (Tittonell et al. 2020). However, despite the potential benefits of alternative agricultural approaches, significant concerns persist regarding their capacity to adequately meet the food demands of the growing global population, especially given challenges like lower yields and increased land requirements (Muller et al. 2017).

The four chosen practices – tillage, mineral fertilization, organic amendments, and cover crops – are key methods for managing soil sustainably. They are well-studied, widely described in research, and remain important because they work in many types of farming and can be combined effectively.

4.1 Tillage

After examining agroecology as a broad approach to sustainable farming, we can focus on conservation agriculture as a practical way to apply these ideas in real farms. Conservation agriculture is becoming more popular because it helps solve many soil problems while still producing good harvests. Unlike traditional farming that relies heavily on plowing the soil, conservation agriculture focuses on protecting soil health through less disturbance, keeps soil covered with organic matter, and uses different crops in rotation. Based on research by Corsi et al. (2012), traditional tillage agriculture, deeply rooted in farming culture, is now recognized as a major driver of soil organic matter depletion and greenhouse gas emissions. Conservation tillage is increasing in popularity as a sustainable agricultural practice (Busari et al. 2015). There are several types of conservation tillage: no-till, reduced tillage, mulch tillage, ridge tillage, and contour tillage. When used correctly, these methods can make soil healthier by improving its structure, increasing organic carbon, reducing erosion, keeping moisture, stabilizing soil temperature, and enhancing overall soil quality (Busari et al. 2015; Topa et al. 2021). However, no-till farming might not help fight climate change as much as people thought. Scientists found that its ability to reduce greenhouse gases is much smaller than expected (Powlson et al. 2014).

Despite these limitations, these methods still have significant potential. Nevertheless, they face several practical challenges. Weed control is one major issue. Without herbicides, organic farmers face increased pressure from grass weeds and perennial species that thrive in less-disturbed soil, making weed control one of the biggest barriers to adopting this environmentally beneficial practice (Peigné et al. 2007).

Another problem is the transition process itself, because when switching from traditional to reduced or no-till farming, farmers should focus on minimizing soil disturbance and keeping crop residues on or near the soil surface (Wezel et al. 2015). During this transition, the soil might become compact, which can limit crop growth and reduce nitrogen availability. In compacted soil, the breakdown of organic matter slows down due to reduced microbial activity, affecting nutrient cycling – here a concern for organic farming systems that rely on nitrogen from legumes and organic manures (Peigné et al. 2007). However, over time, the reduced nitrogen availability can be balanced out by increased organic matter as decomposition slows down.

For successful adoption of conservation agriculture, key factors must be considered - soil physical conditions (structure, drainage), climate parameters, and appropriate selection of cover crops and rotations. Conservation agriculture requires patience, as its benefits become clear only after careful, long-term planning and integrated management of interconnected farming practices (Holland 2004; Stagnari et al. 2009).

4.2 Mineral fertilization

Mineral fertilizers are crucial for modern farming to maintain crop yields. These fertilizers face sustainability challenges, including environmental impacts from excessive nitrogen use and the need for balanced nutrient management. However, Piwowar (2021) indicates that high-volume agriculture is difficult to imagine without them. On the other hand, organic systems rely on slow-release fertilizers, while conventional systems benefit from quick-release mineral fertilizers (Seufert et al. 2012). Mineral fertilizers allow conventional farms to maintain higher yields, while organic farms are often nitrogen-limited (Seufert et al. 2012).

However, the efficiency of mineral fertilizers is concerning - plants only absorb a small portion of applied fertilizers: 50% of nitrogen, 10-25% of phosphorus, and 50-60% of potassium (Lubkowski 2016). This poor absorption rate wastes money and harms the environment, as unused nutrients can flow into water ecosystems, causing pollution and excessive algae growth (eutrophication). With nitrogen fertilizers specifically, nitrates can build up in the edible parts of crops, raising health concerns (Lubkowski 2016).

There are several approaches to reduce our reliance on mineral fertilizers. Some plants, like those in the Fabaceae family (beans and peas), can take nitrogen directly from the air (Zhao et al. 2021). Similarly, certain soil bacteria like *Diazotropha* can capture atmospheric nitrogen (Mohite & Patil 2022).

Mineral fertilization systems led to greater soil organic carbon loss, while organic fertilization approaches resulted in significantly higher soil organic matter content and improved nitrogen, phosphorus and potassium availability (Fließbach et al. 2007; Herencia et al. 2007). Perhaps most promising is combining mineral fertilizers with organic materials like compost, which can maintain high crop yields while improving nutrient absorption and increasing soil organic matter content (Hlisnikovsky & Kunzová 2014).

4.3 Organic Amendment

Adding organic amendments to agricultural soil generally improves soil health. These amendments include various categories: organic fertilizers (such as animal manure and slurry), processed organic waste products (like compost and sewage sludge), plant residues, digestates from anaerobic processes, vermicompost, specialized industrial byproducts, and biochar. However, these materials can pose environmental and human health risks through contaminants including heavy metals, persistent organic pollutants, pathogens, and emerging pollutants such as antibiotic-resistant bacteria and microplastics (Urra et al. 2019). Some amendments like animal manure can cause environmental problems through nutrient leaching and may introduce pharmaceutical residues from animal medicines (Irshad et al. 2013).

Using organic amendments for a long time increases soil carbon storage and helps form soil aggregates (Powlson et al. 2011; Wang et al. 2015;Parmar et al. 2016). These improvements are a long-term investment in soil quality and biological functions (Diacono & Montemurro 2010).

Organic amendments can change soil microbiomes (Drenovsky et al. 2004). One of the most important factors affecting soil's microbial biomass, in terms of diversity and community structure, is the quantity and quality of organic amendments (Tu et al. 2006). According to Bastida et al. (2008), biological indicators like microbial biomass and enzyme activities are particularly useful for detecting improvements in soil quality following organic amendment application, as they respond more quickly to changes than physical soil properties. These amendments can create suppressive soils that naturally fight diseases, by improving soil health, microbial activity, and plant resistance (Cook & Baker 1983; Bailey & Lazarovits 2003; Rosa & Mercado-Blanco 2015).

Organic amendments can store more soil carbon than conservation tillage or cover cropping, showing significant benefits at both shallow (0-15 cm) and deeper (0-50 cm) soil depths, with increases of 26% and 23% of SOC (Crystal-Ornelas 2021). Returning crop residues to soil helps store carbon, form soil aggregates, keep moisture, and reduce erosion (Garbowski et al. 2023).

Composting is an effective method for improving the quality of manure and organic waste. It reduces harmful organisms and enhances the final product by promoting microbial activity and stabilizing organic matter (Hadar & Papadopoulou 2012).

Digestate, the material remaining after anaerobic digestion of organic matter, is another valuable amendment type. Liquid and whole digestate rapidly boost microbial activity, affecting carbon and nitrogen cycling (Monard et al. 2020; Cattin et al. 2021; Meng et al. 2022). Solid digestate tends to be more beneficial for soil biology compared to liquid forms, primarily due to its higher and more diverse carbon content (Fuente et al. 2013; Iocoli et al. 2019). Liquid digestate often boosts bacteria due to its nutrients, but can harm some fungi, though effects vary depending on the digestate and soil conditions. According to van Midden et al. (2023), composting digestate appears to be a potential treatment method that can address several issues.

Vermicompost is an excellent soil amendment. It contains nutrients, hormones, vitamins, enzymes, and humic substances. It creates more microbial diversity than regular compost and works better for soil restoration (Lim et al. 2015). The composition of vermicompost varies based on the starting materials used, affecting its nutrient content, pH, and overall quality as a soil amendment (Ceritoğlu et al. 2018; Elissen et al. 2023).

An uncommon amendment is slaughterhouse waste, which includes materials like blood flour and hoof and horn flour from cattle processing facilities. It has lots of nitrogen and organic matter (da Silva et al. 2019). Bone meal, another by-product consisting of ground animal bones, can reduce heavy metalss in soil, increase pH, and lower toxicity (Hodson et al. 2001).

Also algae work as amendments, biofertilizers, biopesticides, bio stimulants, and soil stabilizers (Khan et al. 2009; Abdel-Raouf et al. 2012). Seaweeds can be used as mulch or compost, though their salt content can cause problems. Algae contain nutrients, amino acids, vitamins, antibacterial substances, and plant hormones (Piwowar & Harasym 2020).

Adding biochar to agricultural soil is considered a useful way to combat climate change whie also improving soil health and crop growth. Long-term experiments have shown that biochar can boost crop yields without harming soil life. It also helps reduce water stress during droughts and improves the soil's structure and nutrient levels (Razzaghi et al. 2020).

4.4 Cover crops

Cover crops significantly improve soil health by enhancing soil fertility, preventing erosion, and improving nutrient and water availability (Sharma et al., 2018). They increase soil organic carbon concentrations in the long term, though these effects may not be detectable in the first few years after establishment (Acuña & Villamil 2014; Blanco-Canqui et al. 2015). Research by Garland et al. (2021) demonstrates that increasing land covered by cover crops improves soil functions and yields in cereal systems more effectively than diversifying rotations.

The selection of cover crops should be based on the farmer's specific objectives, whether preventing soil erosion, enhancing fertility, suppressing pests, improving yields, or achieving other goals. This selection must also consider suitable climate and local growing conditions (Snapp et al. 2005). Farmers should evaluate the functional and morphological traits of different species, as these characteristics determine which environmental benefits they can provide, such as nitrogen fixation from legumes or soil compaction relief from deep-rooted brassicas (Blanco-Canqui et al. 2015).

Using diverse cover crop mixtures instead of single species generally provides better results. For example, Wortman et al. (2012) showed that mixtures with six different plant species grew most reliably, even when bad weather damaged some of the plants.

Cover crops and green manuring are closely related practices in sustainable agriculture. Grean manure means mixing cover crops into the soil while they're still green, usually when flowering. This adds a lot of nitrogen to the soil. Legume plants can add 100-200 pounds of nitrogen per acre, which might reduce or eliminate the need for chemical fertilizers (Rinehart 2025).

No-till practices complement cover crop systems by preserving soil organic carbon. When cover crops are used with minimal soil disturbance, they help maintain soil organic carbon and reduce erosion more effectively than when conventional tillage is used. This happens because plant residues remain on the soil surface longer and decompose more slowly when not incorporated through tillage (Olson et al. 2014).

Permanent crops can benefit from using naturally growing plants or living mulches instead of planted cover crops. Research shows spontaneous vegetation in vineyards can boost grape yields (Raffa et al. 2022). In orchards, living mulches maintain fruit production after an adjustment period and help trees produce more consistently year to year (Sosna et al. 2023). These approaches work differently depending on local conditions but offer ecological alternatives to conventional methods.

When talking about termination, farmers have several options for terminating cover crops beyond chemical methods. Roller-crimpers are particularly promising tools that flatten cover crops to create a protective layer on the soil that holds moisture and blocks weeds (Frasconi et al. 2019; Alonso-Ayuso et al. 2020). Timing is critical – roller-crimping works best when legumes are flowering and grasses are producing seeds (Antichi et al. 2022).

When mechanical termination alone isn't sufficient, combining methods like roller-crimping with other approaches such as flaming can improve results without chemicals (Frasconi et al. 2019). Research by Antichi et al. (2022) found that properly timed termination of hairy vetch could eliminate the need for herbicides like glyphosate in no-till systems. While effectiveness may vary with seasonal conditions and cover crop species (Alonso-Ayuso et al. 2020), these methods offer environmentally friendly alternatives to chemical termination.

Researchers like Van Bruggen et al. (2018) caution that chemical termination methods, particularly glyphosate, may negatively impact soil health by disrupting microbial communities and potentially causing long-term environmental contamination.

5 European Implementation and Adoption Challenges

5.1 Organic farming in the Czech Republic

Since 1990, organic farming in the Czech Republic has grown dramatically, expanding from just 3 farms on 480 hectares to 4,606 farms managing nearly 540,000 hectares by 2018 – representing 14% of the country's agricultural land. By 2023, this trend has continued, with 5,345 farms cultivating over 595,190 hectares, accounting for 16,82% of the total agricultural area (Ministerstvo zemědělství ČR 2024).This growth directly correlates with financial support policies. The first subsidy program (1998-2003) triggered a dramatic increase, with organic acreage moved from 20,000 to 71,000 hectares between 1997-1998. EU accession in 2004 further supported this expansion through agri-environmental measures (Kotyza & Smutka 2021).

The Czech organic sector has a unique land distribution challenge. Unlike the balanced EU pattern, Czech organic land is predominantly permanent grassland (78.70%), with only 20.25% as arable land (Ministerstvo zemědělství ČR 2024). This grassland-dominant model has created an extensive farming system focused on cattle production (64% of all organically raised animals), leading to market saturation in sectors like beef, where only 50% of organic products are sold with organic certification while the rest enter the conventional market due to insufficient organic demand. (Kotyza & Smutka 2021; Ministerstvo zemědělství ČR 2024)

Beyond meat production, Czech organic farms have diversified into dairy, with specialized organic dairy farms operating at high standards and forming marketing cooperatives like "České biomléko." The sector has also seen advancement in crop production techniques, with successful organic vegetable growers, grain producers, and even vineyards thriving without synthetic chemicals. These developments show that organic farming in Czech conditions is unquestionably viable when proper growing techniques and pest management strategies are implemented (Dvorský & Urban 2014).

This approach contributes to promising financial performance, with 98.6% of farms reporting profitability in 2021, partly supported by EU rural development funding. This economic sustainability persists despite lower per-hectare yields (about 50-80% of conventional farms for cereals, and even lower for other crops like potatoes at 49% and oilseeds at 39%) as farmers likely benefit from premium prices and reduced input costs (Hlaváčková et al. 2023).

5.2 Implementation of Conservation Measures and Their Impact

Conservation agriculture is a farming approach that minimizes soil disturbance, maintains permanent soil cover, and practices crop rotation to preserve soil health, with key measures including no-till/minimal tillage, cover cropping, and diversified crop rotations. Conservation agriculture in Europe covers approximately 22.7 million hectares, representing 25.8% of arable land. The countries with the highest proportion of conservation agriculture and no-till practices include: Cyprus 62.1%, Bulgaria 58.0%, Germany 41.1%, and the U.K. 39.2%, Finland 38.7%, Czech Republic 34.8% (Kertész & Madarász 2014).

While conservation agriculture and organic farming represent different approaches to sustainable agriculture, unfortunately newer data for conservation agriculture were not identified. Eurostat (2024) does not directly report specific hectare figures for conservation agriculture as a distinct category, as it focuses more on organic farming, crop types, and general land use. However, to illustrate the broader trend in sustainable farming practices, the total area under organic agricultural production in the EU reached 16.9 million hectares in 2022, up from 15.9 million hectares in 2021 and 14.7 million hectares in 2020. This represents 10.5% of the total utilized agricultural area (UAA) in the EU. Between 2012 and 2022, the organic area increased by 7.4 million hectares (a 79% rise).

European farmers take a gradual approach to conservation agriculture, first trying reduced tillage before fully committing to no-till systems (Lahmar 2010). Rather than adopting all conservation principles at once, farmers tend to select specific practices that work for their situations (Burton et al. 2008). For successful implementation, farmers need to see concrete soil improvements rather than just following prescribed management guidelines. Among 159 organic farmers surveyed across ten European countries, 89% used reduced tillage but only 27% practiced no-tillage, showing selective adoption of conservation methods. Green manures were used by 74%, with higher adoption in Northern Europe (83-96%) than Southern Europe (48%). However, regional climate differences, particularly water availability in the south, influenced which practices farmers adopted (Burton et al. 2008; Peigné et al. 2015).

Cover crops play a crucial role in conservation agriculture by preventing soil erosion while improving nitrogen management and soil quality. Brant et al. (2008) found that cover crops with rapid development and extensive leaf coverage provide superior erosion control benefits. Field trials demonstrate significant environmental benefits: stubble cover crops can produce 1.5-2.5 tons of dry matter per hectare while capturing 40-70 kg of nitrogen that would otherwise leach into groundwater (Haberle & Káš 2007). Danish studies revealed crucifer catch crops reach rooting depths of 1.5m versus 0.6m for ryegrass (*Lolium perenne*), allowing them to capture more nitrogen from deeper soil layers (Thorup-Kristensen et al. 2003). In no-till systems, hairy vetch (*Vicia villosa*) can significantly boost vegetable yields while reducing fertilizer needs, with Campiglia et al. (2014) demonstrating that hairy vetch treatments tripled the yields of sequential vegetable crops compared to other cover crops and performed similarly to plots receiving 50-75 kg/ha of nitrogen fertilizer.

These conservation measures deliver measurable soil improvements, including higher soil organic carbon under no tillage (0.84% versus 0.75% in conventional tillage) and increased earthworm populations (Stagnari et al., 2020). The economic benefits are also substantial, with savings of €234.82 per hectare for no-tillage farms in Spain, primarily through reduced fuel consumption (González-Sánchez et al. 2015).

While the advantages are clear, farmers implementing these practices still face several significant obstacles. Weed control remains a serious challenge in conservation agriculture, along with technical knowledge gaps and equipment limitations (Farooq & Siddique 2015). Building on this, Antichi et al. (2022) showed that carefully timing when to terminate cover crops using roller-crimper machinery can eliminate the need for herbicides in no-till farming, addressing both soil protection and reducing chemical use simultaneously.

Even with these challenges, farms that adopt conservation practices become more resilient. Long-term European research confirms that farming systems using multiple ecological principles – biodiversity, soil organic matter management, and crop rotation – better withstand climate challenges than conventional monocultures. Studies show these systems have improved soil structure and water retention, making them more resilient to both droughts and floods (Niggli et al. 2008). These findings support the conclusion that agroecological approaches can succeed at various production scales, challenging the notion that sustainable soil management only works in small-scale settings. For example, a large-scale farm in Flevoland, Netherlands (EU) successfully implements diverse grasslands, biodiversity corridors, and adapted breeding while maintaining high milk productivity (Tittonell et al. 2020).

5.3 Barriers to Adoption

Despite evident benefits, significant barriers hinder adoption of sustainable agricultural practices. Economic factors represent major obstacles to adoption. High initial costs often discourage farmers from transitioning to agroecological methods, while perceived financial risks and uncertainties about yield reductions or market uncertainties create further hesitation (Gemtou et al. 2024). Long et al. (2016) identified high initial costs, uncertain returns, and uneven distribution of financial risks across the supply chain as key barriers to climate-smart agriculture technologies in Europe.

Pedersen et al. (2024) highlight a lack of strong financial incentives and farmers' tendency to prioritize short-term benefits over long-term sustainability. This focus on immediate gains is reinforced by market pressures driving short-term profit maximization, creating a gap between immediate income needs and long-term environmental benefits. Serebrennikov et al. (2020) found that farmers' economic attitudes, particularly preferences for increasing farm profit, negatively affect their likelihood of adopting organic practices.

Pagliacci et al. (2020) suggest that current financial support systems need restructuring to better accommodate different farm types and local conditions, though implementing such changes presents challenges.

Policy-related barriers also limit adoption of sustainable practices. Pedersen et al. (2024) note that inadequate policy frameworks and insufficient extension services leave farmers without necessary guidance and resources to implement sustainable methods. Despite efforts like the European Union's Common Agricultural Policy to promote sustainability, Brown et al. (2021) argue that existing frameworks often overlook important non-economic factors that influence farmer decisions.

The bureaucratic complexity and rigidity of agricultural support schemes can discourage participation in agroecological programs. Gemtou et al. (2024) emphasize that administrative burdens associated with applying for subsidies and navigating certification processes can be overwhelming, particularly for smallholders.

Barnes et al. (2019) propose that indirect support measures, such as providing information resources and demonstrating the economic viability of sustainable practices, may help bridge the gap between policy goals and on-farm implementation.

Social factors significantly shape farmers' decisions to adopt sustainable practices. Dessart et al. (2019) emphasizes the importance of social norms and peer influence in adoption decisions. Farmers are heavily influenced by peer behavior, and social networks can either facilitate or hinder adoption of new practices. Resistance to change presents another significant barrier, with many farmers hesitant to deviate from established practices, especially those passed down through generations (Gemtou et al. 2024).

Knowledge gaps further impede adoption of sustainable methods. Farmers' attitudes toward sustainable practices are largely shaped by their understanding of the benefits and implementation requirements (Zeweld et al. 2017). Generally, farmers with greater access to information and education show more willingness to adopt innovative practices.

Technological complexity presents another barrier. Many farmers lack technical knowledge or training required to implement sophisticated techniques like precision agriculture (Barnes et al. 2019). High upfront costs for new technologies present additional hurdles, particularly for small-scale farmers. Yigezu et al. (2018) found that when farmers were required to purchase expensive equipment outright, adoption rates remained low, but increased significantly when provided free initial access and hands-on training.

6 Conclusions

This thesis successfully met its objectives to investigate soil properties and agroecological practices, evaluate sustainable farming approaches, provide European case studies, and offer implementation insights. While extensive research exists on soil indicators and sustainable practices, more studies are needed on their practical application at larger scales.

The analysis found that soil health depends on interconnected physical, chemical, and biological properties. Chemical indicators like soil organic carbon and pH affect many soil processes, serving as the foundation for nutrient availability. These chemical properties directly influence physical properties such as aggregate stability, which in turn determine soil structure and water management. Together, they create environments where biological indicators thrive - from earthworms restructuring the soil to microorganisms driving nutrient cycling, forming a complete living ecosystem.

The review identified four beneficial agroecological approaches. Conservation tillage improves soil structure and reduces erosion, though weed management remains challenging. Mineral fertilization supports crop yields but is inefficient, with only 10-60% of nutrients used by plants. Organic amendments including compost, digestate, vermicompost, and biochar enhance soil carbon and biological activity while improving water retention and drought resistance. Cover crops prevent erosion and improve nitrogen management, especially when diverse species are used with appropriate termination strategies.

In Europe, the research found notable progress alongside challenges. The Czech Republic has expanded organic farming to 16.82% of agricultural land, though mainly as grassland for cattle rather than crop systems. And in the EU total area under organic agriculture reached 16.9 million hectares in 2022, representing 10.5% of the total utilized agricultural area, with a significant 79% increase since 2012. However, data on conservation agriculture implementation across Europe vary between sources and are limited.

Importantly, farming systems using multiple ecological principles demonstrate greater resilience to climate challenges than conventional monocultures, better withstanding both droughts and floods. Studies show that agroecological approaches can succeed at various production scales, challenging the notion that sustainable soil management only works in small-scale farms.

Despite benefits, farmers face adoption barriers. Economic concerns include high initial costs and uncertain returns, with a disconnect between short-term economics and long-term sustainability benefits. Inadequate policy frameworks and excessive bureaucracy limit participation in agroecological programs. Social resistance to change impacts adoption decisions, while knowledge gaps and technological complexity create additional hurdles, especially for smaller farms.

Agroecological practices offer practical ways to manage soil that balance farm productivity with environmental protection. For these practices to become more widespread, better cooperation is needed between policymakers, researchers, and farmers. This requires creating appropriate incentives, improving access to technologies, and effectively sharing knowledge. With additional research and support that addresses both current challenges and long-term benefits, sustainable soil management can become standard practice, preserving this essential resource for future generations.

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