Enhancing Biological Soil Health through Land Management Change

A Case Study of Small-scale Market Gardening in Southern Sweden

Leòn Pepe Biundo

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Swedish University of Agricultural Sciences, SLU
Faculty of Landscape Architecture, Horticulture and Crop Production Sciences
Department of Biosystems and Technology
Horticultural Sciences – Master´s Programme
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Abstract

With conventional food production systems incapable of meeting the increased global food demand, restoring soil health, and mitigating the climate crises—a paradigm shift towards sustainable agricultural practices is urgently needed. This study explores the efficacy of biointensive market gardening, a management approach emphasizing agroecological sustainability, as an alternative to conventional methods. Employing organic market gardening management on previously agricultural land, this research offers a comparative analysis of biological soil health with organic conventional production and a natural reference system. Results reveal significant enhancements in soil health parameters, including soil organic matter, protein content, bulk density, nutrient availability, and microbial parameters like respiration, fluorescein diacetate hydrolysis (FDA) and active carbon in the market gardening system compared to agricultural system. Notably, the market gardening system surpassed natural benchmarks in multiple parameters and showcased resilience against climate variability. Consequently, the study underscores the potential of market gardening in strengthening agricultural resilience, improving soil health, and ensuring future food security, aligning with the United Nations' Sustainable Development Goals.

Keywords: sustainable food production, soil health, market gardening, agroecology, conservation agriculture, CASH protocol

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Abbreviations

AAF	Alnarp´s Agroecology Farm
CA	Conservation agriculture
CASH	Comprehensive Assessment of Soil Health – manual
CSA	Community supported agriculture
EU	European Union
F	Field system = organic agricultural system
FAO	Food and Agriculture Organisation of the United Nations
FDA	Fluorescein diacetate
K	Potassium
MG	Market gardening system
N	Natural system = fence line
Nmin	Plant available nitrogen
Norg	Organically bound nitrogen
P	Phosphorus
SOC	Soil organic carbon
SOM	Soil organic matter
SLU	Swedish University of Agricultural Sciences

1. Introduction

1.1 Global context

In the face of climate change and rapid global population growth, projected to approach 10 billion people by the year 2050, the demand for sustainable and resilient food production systems has become more pressing than ever before (EU, 2023). However, the prevailing paradigm in horticultural and agricultural industries leans heavily towards industrialized, high-tech, input-dependent production methods, relying on non-renewable resources such as synthetic fertilizers and fossil fuels (Morel and Léger, 2016). Driven by global markets, this productivity-focused approach, though yielding short-term gains, comes at a significant cost to our natural ecosystems, biodiversity, and the climate, threatening the food security of future generations (Tilman et al., 2002). By the definition provided by the United Nations Committee on World Food Security, food security guarantees all individuals, without exception, continuous access to adequate, safe, and nutritious food, fulfilling their dietary requirements and preferences for an active and healthy existence, including physical availability, social accessibility, and economic affordability of food resources at all times (FAO, 2008). Thus, the urgency to address this challenge and simultaneously steer towards a sustainable future necessitates a paradigm shift in our food systems and agricultural practices (Tittonell, 2014).

Defining sustainable agriculture presents challenges due to the diverse and interconnected environmental, social, and economic influences that agriculture encompasses. Nevertheless, sustainable crop production systems can be characterized as those that prioritize environmental stewardship, optimize resource utilization efficiency, and foster human well-being (Tilman et al., 2002). Such practices integrate ecological, biological, physical, and chemical principles, with a key focus on environmental preservation (Tittonell, 2014).

Soil constitutes the predominant surface material covering a vast portion of land, comprising both inorganic particles and organic matter. It plays a pivotal role in providing structural support to agricultural plants, serving as their primary source of essential nutrients and water (Moebius-Clune et al., 2017). The soil ecosystem provides several ecosystem functions like carbon sequestration, nutrient cycling, plant growth support, detoxification, and water retention (Figure 1). Thus, a functioning soil ecosystem provides essential ecosystem services to humanity, up front the production of food, feed, fibre, and fuel, but also biodiversity, erosion control, water purification, and climate change mitigation (Power, 2010).

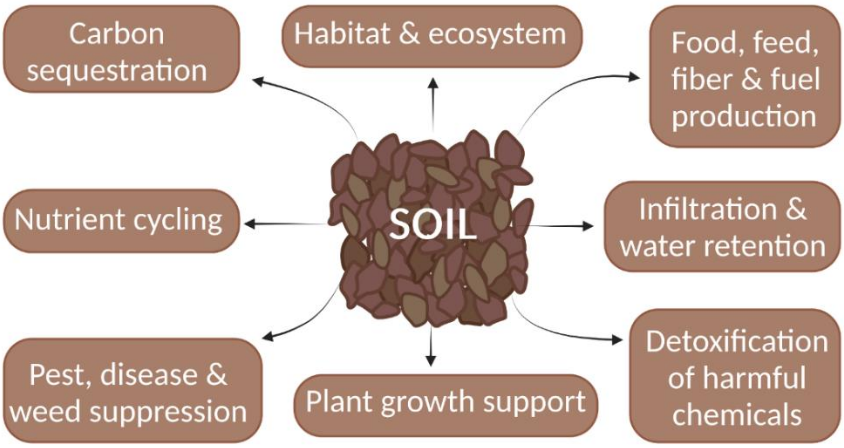


Figure 1: Display of the main functions of soil as a living medium in the context of sustainable agriculture. Taken and modified form Moebius-Clune et al. (2017), created with BioRender.com.

1.2 Constrains of conventional agriculture

Intensive use of chemical inputs and machinery in conventional tillage practices are classified as degrading land-management practices (Power, 2010, Tilman et al., 2002). In long-term, such practices are known to disturb soil structure (Page et al., 2020), contribute to increased erosion (Rillig et al., 2019), oxidation of soil organic matter (Tilman et al., 2002) as well as nutrient losses (Lal, 2015). Adversely affected soil quality parameters like organic carbon content (Sahu et al., 2020), bulk density (Sekaran et al., 2021), water holding capacity (Page et al., 2020), nitrogen availability (Sahu et al., 2020) microbial community structures (Rillig et al., 2019) and biochemical activity (Power, 2010) lead to decreased overall crop yields (Page et al., 2020). Additional constraints associated with conventional agriculture could be limited ecosystem functionality resulting in the loss of essential ecosystem services, higher input dependency and less healthy production systems (Schröter et al., 2005). Altogether, the degradation of productive agricultural land in combination with the loss of agroecosystem functionality threatens future food security objectives (Figure 2).

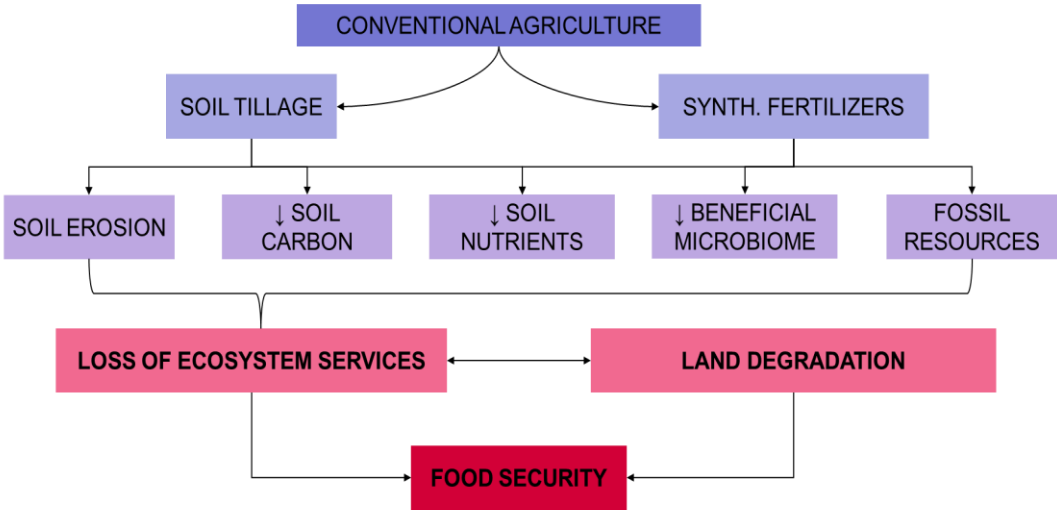


Figure 2: Environmental impacts of conventional agriculture. Especially the utilization of soil tillage as well as chemical fertilizers has a detrimental impact on the agroecosystem, resulting in soil quality degradation and the loss of essential ecosystem services over time. Decreased agroecosystem functionality combined with increased land degradation threatens future food security objectives. Taken and modified from Cárceles Rodríguez et al. (2022) edited with BioRender.com.

1.3 Soil health and sustainable agriculture

To contrast the negative impacts associated with conventional agriculture (Figure 2), a search for sustainable production methods has emerged globally. Within this explorative journey for viable agricultural solutions, the concepts of "soil health" and "soil quality" are gaining widespread recognition (Moebius-Clune et al., 2017). A contemporary consensus defines soil health as "the continued ability of the soil to function as a vital living ecosystem that supports the well-being of plants, animals, and human beings" (Doran and Zeiss, 2000). Soil quality is composed of soil biological, physical, and chemical properties which can be divided into “inherent” and “dynamic” quality. The first describes the inherent composition and properties of a soil, which are shaped by geological and long-term environmental factors and processes, which generally remain beyond the scope of human influence (Moebius-Clune et al., 2017). Aligning with Rosberg and Alsanius (2022), dynamic soil quality, synonymous with soil health, encompasses soil characteristics that undergo changes due to soil utilization and land-use management within the human time scale. According to Lal (2016), the concept of soil health recognizes soil as a vibrant ecosystem comprised of physical, chemical and biological parameters, which reacts to management practices. Important physical parameters are soil depth and tilth, as well as water storage and drainage capacity (Lehmann et al., 2017). Sufficient nutrient supply and non-toxic heavy metal concentrations represent important chemical parameters while essential biological parameters are low pathogen activity linked with a strong beneficial microbiome as well as low weed pressure on the system (Moebius-Clune et al., 2017). Overall systematic resistance and resilience against biotic and abiotic stressors is a result of healthy cropping conditions, which necessitates careful management to restore and sustain its optimal soil ecosystem functionality (van Bruggen et al., 2006).

The core pillars of soil health management include (1) minimizing soil disturbance by non-destructive farming practices like no-till or no-dig; (2) maximizing biodiversity promoting farming methods like cover cropping and crop rotations; (3) encouraging permanent soil cover which in return provides (4) maximized living roots in the soil, increasing soil organic matter and fostering microbial activity (Daverkosen et al., 2022) (Figure 3). Consequently, farmers are effectively sequestering higher levels of carbon, enhancing water infiltration rates, ameliorating wildlife and pollinator habitat conditions — achieving these outcomes

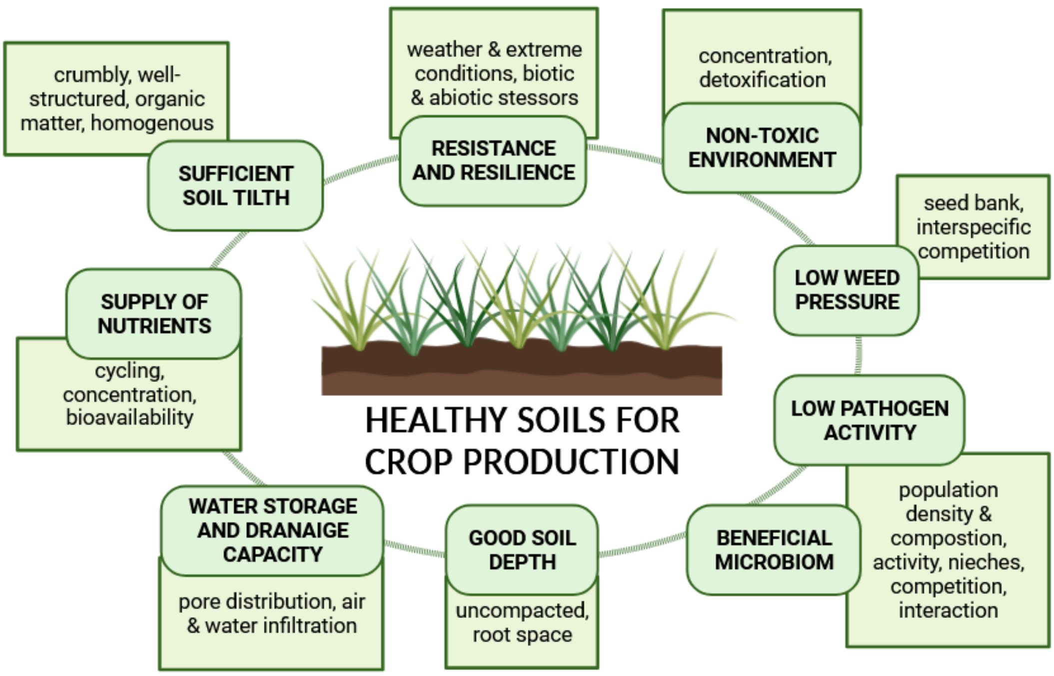


Figure 3: Characteristics of healthy soils for crop production, as sufficient soil health is not a given in conventional management practices but essential for future sustainability of agricultural operations. Taken and modified from Moebius-Clune et al. (2017), edited with BioRender.com

while realizing enhanced profits and often improved yields (Page et al., 2020). Thus, the potential of reversing unfavourable soil conditions resulting from conventional agricultural practices through modified long-term management and dedicated environmental stewardship appears to be feasible (Lehmann et al., 2017, Lehmann et al., 2020a, Lehmann et al., 2020b, Rillig et al., 2019).

1.4 Importance of soil organic matter for biological soil health

Soil organic carbon (SOC) is of essential importance in the context of sustainable agricultural advancement, environmental preservation, and soil fertility enhancement – it is regarded as the cornerstone of agroecosystem functionality (Lal, 2004). SOC represents the carbon content stored within soil organic matter (SOM) (Moebius-Clune et al., 2017). The incorporation of SOC into the soil occurs because of decomposition processes involving crop residues also including well stabilized materials, root exudates, both living and dead microorganisms (bacteria, fungi, and protozoa) as well as amendments containing biomass, such as different types of manure, mulching materials and composted organic matter (Moebius-Clune et al., 2017, Sekaran et al., 2021).

Soil organic matter exert substantial influence over the physical, biological, and chemical attributes of the soil medium, persistently sequesters carbon in the soil and operates as a gradual release reservoir for nutrients (Page et al., 2020). It substantially contributes to ion exchange capacity, thereby facilitating nutrient retention and cycling, soil aggregation, and improves the water holding capacity (Moebius-Clune et al., 2017). Furthermore, SOM serves as a source of nutrients and energy for both plant and soil microbial communities (Page et al., 2020).

Soils containing high levels of SOM tend to exhibit reduced demands for agricultural inputs and enhanced resilience in the face of abiotic stressors like drought or excess water (Rahman et al., 2021, Davis et al., 2023). As organic matter content rises, soil tilth ameliorates, leading to reduced compaction and increased pore space for improved air circulation and water retention, further translating into improved soil porosity, facilitating unrestricted root development due to improved soil matrix access to oxygen, water, and nutrients (Page et al., 2020).

Enhanced SOM levels contribute to the establishment of a beneficial environment for microbial communities, attributed to the refinement of soil aggregation, optimization of soil moisture content as well as more steady soil temperatures (Page et al., 2020, Lehmann et al., 2017). Consequently, soil microbial abundance increases (Sahu et al., 2020). The enhanced prevalence and diversity of microorganisms can promote agricultural productivity due to higher functional diversity providing plant growth promotion and disease suppression (Page et al., 2020, Deguine et al., 2023).

Thus, the management related accumulation of SOM has an essential impact on the biological soil health status, which in turn plays a critical role in the context of sustainable food production and global food security (Lal, 2004).

The diverse community of microorganisms, fungi, and macrofauna, living in healthy soils plays a crucial role in providing important ecosystem functions for resilient production systems (Lehmann et al., 2020b) (Figure 1). Soil structure formation is achieved especially by saprotrophic fungi through the secretion of extracellular compounds and the physical binding of soil particles facilitated by their hyphal networks, improving soil aggregation and water storage capacity (Ray et al., 2020, Lehmann et al., 2020a, Rillig et al., 2019). Other soil microorganisms, bacteria, nematodes and fungi, pray on pests and pathogens, mediate the conversion of nitrogen (N) from inorganic to organic compounds, provide plant available forms of phosphorus (P), and other essential minerals for plant growth, thereby impacting overall plant health as well as productivity (M. Tahat et al., 2020, Page et al., 2020, Behnke et al., 2021). These intricate biological processes are closely intertwined with the land-use and land-management practices shaping the agroecosystem (Lehmann et al., 2020b, Daverkosen et al., 2022).

In summary, the abilities of microbial communities, including remediation of harmful chemicals, soil aggregation, nutrient mobilization, fixation and cycling, as well as the decomposition and degradation of (in)organic matter establish a link between functional microbial communities, the promotion of soil health and agricultural sustainability (M. Tahat et al., 2020).

1.5 Conservation agriculture

Conservation agriculture (CA) constitutes a systematic agricultural approach that promotes a combination of no tillage with maintained soil cover, always providing living roots in the soil (Lehmann et al., 2020b, M. Tahat et al., 2020). In essence, CA represents an agricultural framework structured to decrease reliance on external inputs and focus on the sustainability of agricultural productions by protecting soil, water, and biological resources (Page et al., 2020).

Numerous global examples substantiate the potential of organic conservation agriculture as a sustainable production approach to counteract the impacts of mainstream conventional agriculture on soil health (Figure 2), preventing soil degradation, and safeguarding food security (Alsanius et al., 2023, Montgomery and Biklé, 2021, Rahman et al., 2021, Rosberg and Alsanius, 2022). CA methods are expected to cause minimal physical soil disturbance, the utilization of cover crops and crop rotations supports soil carbon sequestration, while species diversification leads to higher biodiversity (Figure 4). All three methods increase soil health with positive effects on the physical, chemical, and biological attributes of soil, providing climate change mitigation as well as preserving the agroecosystem's capability to supply essential ecosystem services (Lal, 2015, Lal, 2004, Tilman et al., 2002).

Especially enhanced long-term retention and accumulation of organic matter is fostered through strategies that alter the impact and frequency of tillage, like no-till and no-dig methods (Page et al., 2020). Additionally, consistent incorporation of diverse organic matter from various sources (such as amendments, residues, and cover crops, particularly their roots) serves to stimulate microbial community proliferation and the sequestration of carbon within aggregates (Sekaran et al., 2021, Sekaran et al., 2020). Reduced tillage productions allow for physico-chemical stabilization of soil aggregates through undisturbed interactions between SOM and the soil structure, reducing the loss of SOM through microbial respiration or erosion (Lehmann et al., 2020a).

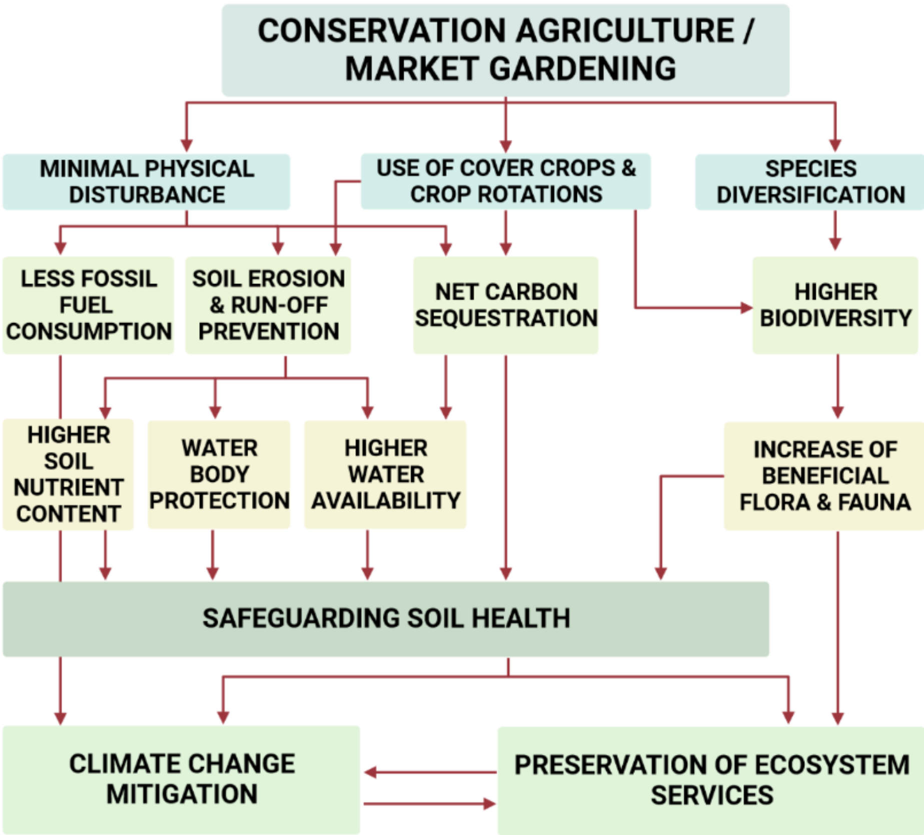


Figure 4: Expected environmental benefits provided by conservation agriculture methods, including market gardening. Taken and modified from Cárceles Rodríguez et al. (2022), edited with BioRender.com.

Thus, effective soil aggregation is correlated with SOM levels, but also diversity and abundance of soil microorganisms, soil fertility and other soil functions like water and air infiltration, water retention, as well as nutrient availability (Sekaran et al., 2020, Sekaran et al., 2021) (Figure 4).

1.6 Agroecology as an inspiration

Agroecology, as envisioned by Gliessman (2013), is a holistic and interdisciplinary approach to agriculture that emphasizes the integration of ecological principles and social considerations in farming practices. It seeks to create sustainable and resilient agricultural systems that are in harmony with nature and benefit local communities (Tittonell, 2014). By promoting biodiversity, reducing reliance on external inputs, and enhancing ecological interactions, agroecology fosters self-regulating and diverse agroecosystems (Mockshell and Kamanda, 2018). Importantly, agroecology acknowledges the interconnectedness of ecological, economic, and social aspects of farming, valuing traditional knowledge and farmer participation in decision-making processes (Pépin et al., 2021). The scope of agroecology offers a transformative path towards sustainable and equitable food systems, safeguarding the environment, and nourishing communities (Tittonell, 2019).

In the context of conversion agriculture, the emergence of low-input, low-tech production systems have become essential to rival the conventional high-input, highly technologized, big scale regime (Drottberger et al., 2021). A promising approach can be found in the growing social movements centred around "market gardening" which are strongly linked to the principles and frame works of agroecology (Pépin et al., 2021).

1.7 The potential of market gardening

Market gardening embodies the agroecological perspective, promoting a sustainable and regenerative approach to agriculture (Drottberger et al., 2021). By emphasising on methods suitable for low-tech small-scale, intensive productions, the approach focuses on diversity, ecological balance, and community engagement (Fortier et al., 2014). With its emphasis on locally-grown produce and short food supply chains, market gardening reduces the carbon footprint associated with transportation, supports local economies, and meets the demands of the interacting local communities (Drottberger et al., 2021). The combination of agroecological principles with those of organic productions (Figure 4) is suggested to lead to environmental stewardship and long-term sustainability (Pépin et al., 2021).

In market gardening as promoted by Fortier et al. (2014) "no-dig” soil management plays the central role in the soil-human-interaction. This methodology differs from conventional agricultural practices by advocating minimal soil disruption. Aeration of the soil before cultivation is recommended while mixing of different soil layers is avoided. Additionally, it emphasizes the use of organic matter such as compost, cover crops, and mulches to nurture a thriving soil ecosystem. By creating a stable and undisturbed soil environment, no-dig market gardening provides a favourable habitat for a wide diversity of bacteria and fungi (Sekaran et al., 2020, Rosberg and Alsanius, 2022). The reduced disturbance of soil helps maintain the intricate networks of fungal hyphae and bacterial colonies that exist within the soil structure (Kim et al., 2020). This preservation of microbial habitats enables a thriving community of microorganisms to develop and provide the essential ecosystem functions needed in healthy production systems (Figure 3) (Daverkosen et al., 2022, Rosberg and Alsanius, 2022).

In summary, market gardening aims to achieve a harmonious integration of agricultural productivity and environmental preservation, directing production systems towards enhanced sustainability and resilience (Drottberger et al., 2021). Thus, the potential of transitioning the land-management from conventional tillage practices to no-dig market gardening methods represents a promising avenue for agricultural systems to unlock their full functional potential again (Mangalassery et al., 2015).

1.8 Biological soil health assessment

The utilization of biological soil health indicators, as outlined in the "Comprehensive Assessment of Soil Health" (CASH) manual by Cornell University (Moebius-Clune et al., 2017), holds significant relevance for agricultural and environmental studies (Lehmann et al., 2020b). These indicators offer a comprehensive understanding of soil ecosystems by examining the diversity, activity, stability and functional composition of soil microorganisms (Davis et al., 2023). By assessing parameters such as soil respiration, enzyme activity, microbial biomass, SOM and other relevant markers, the CASH manual provides direct proxies for the soil's vitality, nutrient cycling efficiency, and overall health (Lehmann et al., 2020b). The adoption of such indicators is crucial in evaluating the impact of land-use management changes, particularly in the context of transitioning towards sustainable and ecologically sensitive practices (Davis et al., 2023, Lehmann et al., 2020b). Furthermore, these indicators support the holistic assessment of soil quality changes, enabling informed decision-making for agricultural systems that are directed towards environmental stewardship, biodiversity conservation, and sustainable food production (Doran and Zeiss, 2000).

1.9 Research Objectives

This research project aims to uncover the potential of small-scale, no-dig market gardening as a sustainable production method and its implications for biological soil health indicators. Despite being a promising land-management approach, knowledge about its ability to enhance or generally impact soil health, microbial activity, nutrient cycling, and soil organic matter content remains limited within academia. Considering the United Nations Sustainable Development Goal 12 on responsible consumption and production (UN, 2015), this research intends to bridge this knowledge gap between land-management change (SDG 12), sustainability efforts (SDG 13), and the critical need for food security (SDG 2 & 3). Therefore, the objective of this research project is to investigate the transformative potential of no-dig market gardening concerning biological soil health. Furthermore, to contribute to a foundation for a resilient and ecologically harmonious future in the realm of food production by deepening the understanding of the interconnectedness between land-use management, biological soil health, and broader sustainability goals.

1.10 Research Questions

The research aims to address the following sub questions: (a) How does the transition to no-dig market gardening affect the biological soil health parameters: microbial activity (microbial respiration, FDA, and soil protein), SOM content, and active carbon. (b) What is the impact of land management change on the additional soil parameters bulk density and nutrient availability. (c) Is there a correlation between the SOM and microbial activity? (d) Can the adoption of no-dig market gardening lead to increased SOM and other biological soil health parameters, offering a sustainable approach to production intensification (SDG 2, 3 12 and 13)?

1.11 Hypotheses

1. Market gardening, as compared to machine-managed organic land management increases SOM contents, thus leading to higher microbial activity.
2. The implementation of no-dig, highly intensive market gardening heightens further soil health parameters when compared to machine-managed organic land management.

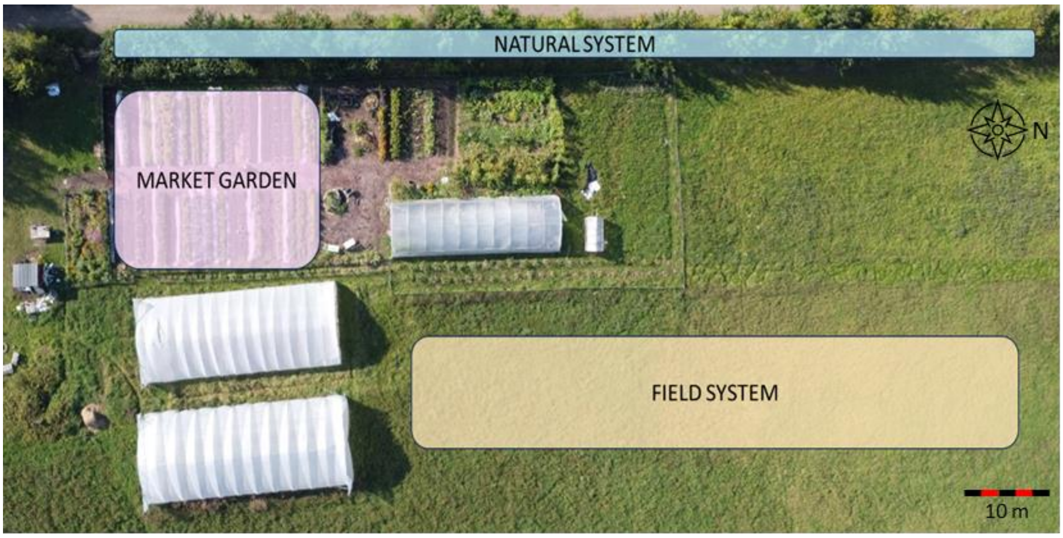
2. Case study and methods

2.1 Experimental site

2.1.1 Market Garden system

The market gardening system is part of the student-operated Alnarp's Agroecology Farm (Picture 1). The Alnarp´s Agroecology Farm (AAF) at was established in 2022, cultivating a productive area of 1400 m2 following market gardening principles, dedicated to supplying fresh vegetables for 15 weeks annually to a local community comprising of 30 CSA members and 100+ market customers.

The AAF's bio-intensive market gardening production regime incorporates a diverse array of over 40 annual cultivars to ensure a continuous harvest from June to mid-October (about 20 weeks of production). No-dig soil aeration was done with every successional crop change over before planting the next crop. The soil was broken up and aerated using a broad fork (40 cm deep), without turning or mixing



Picture 1: Aerial picture of the sampling site at Mellangård, Alnarp in Southern Sweden. The market gardening area (pink) is part of the Alnarp´s Agroecology Farm, which is situated on the KRAV certified research field managed by Alnarp´s Egendom. The field system (yellow) is part of this organically managed research field. Both, the market garden as well as the field system are surrounded by an unmanaged fence line, representing the natural system (blue).

the soil. The seed bed (top 5 cm) was prepared using a hand operated cultivator. Compost mulching was used to suppress weeds, to store water, and slowly-release nutrients for soil microorganism. Thus, a layer of organic compost was applied to the beds early in the season, 15 cm of compost in 2022 and 10 cm in 2023 respectively. Fertilization was carried using either a solid medium-release organic plant-based fertilizer (OPF 11-0-5, semenco.se) or a self-made fermented liquid fertilizer. The first had a NPK ratio of 11-0-5 and was applied four times during the production period at a rate of 65g/m^2. The latter was created from fermented herbs (e.g., nettles, horse tail, comfrey etc.) picked from the local environment. The herbs were chopped and mixed with water, allowing naturally occurring microorganisms to break down organic matter and release essential nutrients during a fermentation period of 2 to 4 weeks. The resulting liquid fertilizer was diluted 1:10 with water and applied to all crops every other week during the production at a rate of 3.35 l/m^2.

The Alnarp´s Agroecology Farm's primary soil characteristics were typified by loamy texture, predominantly attributed to the presence of tertiary limestone bedrock.

2.1.2 Field system

The field system was part of a 4 ha KRAV certified research site managed by Alnarp's Egendom in cooperation with SLU Alnarp. Soil management employed mechanized techniques, utilizing equipment like tractors, ploughs, and cultivators of different, specialized kinds. The crop rotation sequence applied by Alnarp's Egendom on Mellangård during the research period included winter wheat (2021 – 2022, Picture 2, Appendix 1) and a grass legume ley (2022 – 2023, Picture 3 – 5, Appendix 1). During the research period the field system received no further soil management since the grass legume lay was already sown in with the winter wheat in autumn 2021. Thus, apart from harvesting the winter wheat in late summer 2022 the soil of the field system stayed undisturbed. Due to a low germination rate of the grass legume ley in 2023 (Picture 4, Appendix 1), the field was mown in June 2023 to decrease the weed pressure.

2.1.3 Natural

The natural system was represented by an unmanaged fence line bordering the AAF and the agricultural field production (Picture 1). The establishment of the wire fence is more than 20 years ago, since then multiple tree and bush species have self-established on either side of the fence (4 m width in total). Vegetation is dominated by species like *Prunus avium, Fraxinus excelsior, Betula alba, Ulmus campestris* and *Rosa canina*. Subject of research were three *Rosa canina* bushes throughout the research period 2022 -2023 (Picture 2-5, Appendix).

2.1.4 Experimental setup

Soil samples were collected at four occasions: 21.06.2022, 13.10.2022, 17.04.2023 and 24.08.2023 in the three research systems: organic market garden (MG), organic agricultural field system (F), and the unmanaged, natural fence line (N). Each system was divided into three blocks . The soil sampling was conducted using a hand soil auger, sampling to a depth of 40 cm. Eight soil cores were taken in each block. These were thoroughly mixed in a bucket to homogenize the sample. Approximately 1.5 kg of soil per block was collected in a plastic bag and transported to the laboratory for analysis. Samples were screened and homogenized with a 2 mm soil screen. For later microbial analysis 3 subsamples per block were taken and stored at -20°C. Some soil was set aside to air-dry, the rest was stored at 4°C until needed.

Table 1: Presentation of the growing crops present at the sampling dates.

	21.06.2022	13.10.2022	17.04.2023	24.08.2023
MG	Lettuce	Lettuce	Winter oats	Lettuce / pak choi
F	Winter wheat in-sown with ley	Grass-legume ley, rye stubbles	Grass-legume ley, rye stubbles	Grass-legume ley, weeds
N	Wild rose bush	Wild rose bush	Wild rose bush	Wild rose bush

Different crops were present at the sampling dates in the research systems MG, F, and N during the research period (Table 1). In the MG system, lettuce was present on 21.06.2022 and 13.10.2022, followed by a shift to winter oats on 17.04.2023, and a combination of lettuce or pak choi on 24.08.2023 (Picture 2- 5, Appendix 1). The F system displayed variations in plant composition, with winter wheat in-sown with grass-legume ley on 21.06.2022, transitioning to a grass-legume ley with wheat stubbles on 13.10.2022, and maintaining a grass-legume ley on both 17.04.2023 and 24.08.2023. In the N system, the subject of research were three individual wild rose bushes.

2.2 Climatic conditions

The AAF is situated within a temperate maritime climate characterized by an average annual temperature of 9.7°C and an average annual precipitation of 513.2 mm (Lantmet, 2023). August and September experience the highest rainfall in the season, January and February usually represent the coldest months and July emerges as the warmest month of the year. Notably, the farm's proximity to the Baltic Sea contributes to the stability of yearly average temperature (Figure 5).

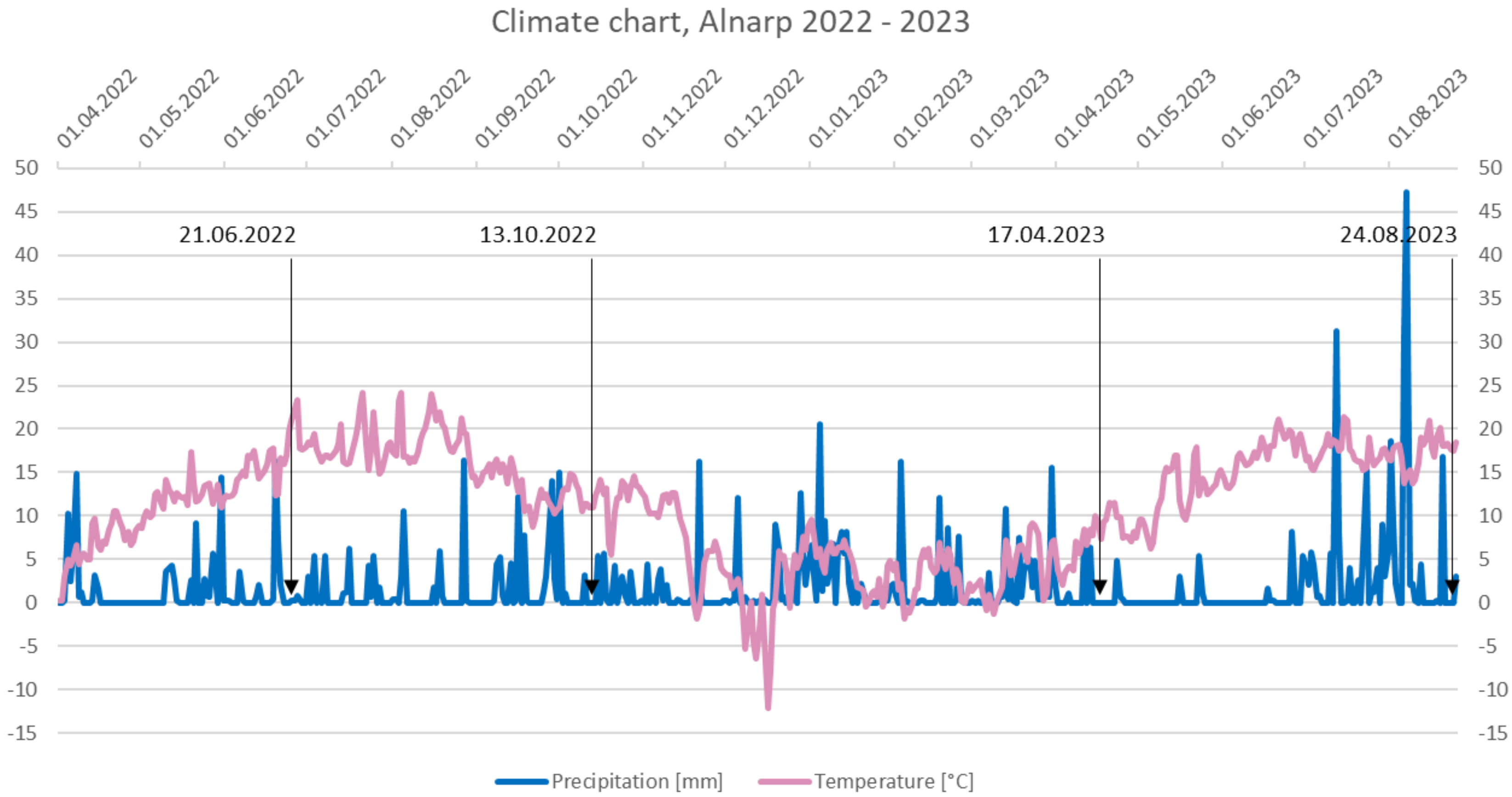


Figure 5: Combined precipitation (blue) and temperature (pink) chart for Alnarp, Sweden. The collected data covers the research period starting in April 2022 until the 25.08.2023. The four sampling events are indicated with arrows displaying the sampling date. The sampling was done in dry conditions, following precipitation events. The data was provided by Landmet (2023).

2.3 Biological soil health indicators

The biological soil health indicator analysis as well as all calculations (unless stated otherwise) were performed according to the CASH protocol provided by Moebius-Clune et al. (2017), except for the analysis of microbial activity which followed which was conducted based on Green et al. (2006)..

2.3.1 Microbial respiration

A total of 20.00 g dried and sieved soil was weighed into an aluminium weighing boat (Ø 6.5 cm, 4 cm hight), which had been pre-perforated with 9 pin-holes through the bottom. The weighing boat, along with the soil, was positioned atop two stacked filter papers (Whatman Nr. 2) placed at the bottom of a standard 500ml wide-mouth mason jar. A trap assembly, consisting of a 10 ml glass beaker secured to a wire tripod was inserted into the jar over the soil containing weighting boat. The beaker was filled with 9 ml of 0.5 M KOH (CO_2-trapping solution). Additionally, 7 ml of distilled, deionized water was pipetted into the jar, allowing the water to be led up into the soil through the filter paper. The jar was then sealed tightly and left undisturbed for a period of 72 hours. Following the incubation, the jar was opened, and the conductivity of the trap solution was measured using a Hach 440d multi conductivity meter. The amount of CO_2 respired was calculated by comparing the trap solution's conductivities with those of the original solution and a solution that simulated trap saturation with CO_2 (0.25 M K_2CO_3).

2.3.2 Fluorescein Diacetate Analysis (FDA)

1 g of air-dried soil was placed in a 125 mL Erlenmayer flask. Then, 50 mL of 60mM sodium phosphate buffer ($Na_3PO_4*12H_2O$, pH 7.6) and 0.5 mL of 4.9 mM FDA lipase substrate solution ($C_{24}H_{16}O_7$ in reagent-grade acetone) were added. A stopper was placed in the flask, and its contents were swirled for a few seconds to ensure homogenous mixing. Subsequently, the flask was placed in an incubator for 3 h at 37 °C.

After incubation, 2 mL of reagent-grade acetone were added to the suspension, and the contents were swirled to terminate FDA hydrolysis. About 30 mL of the soil suspension was transferred to a 50 mL centrifuge tube, which was then centrifuged at 8000 rev min^{-1} (8820g) for 5 min. The supernatant was filtered through a Whatman No. 2 filter paper, and the filtrate was transferred to a colorimeter tube. Absorbance was measured on a spectrophotometer (Hach DR3900) at 490 nm.

To calculate the amount of fluorescein in the soil from the obtained absorbance values, a standard curve (Appendix 1, Figure 18) based on known concentrations of fluorescein was produced. Utilizing the equation of the standard curve the amount of fluorescein (mg/g soil) was calculated according to the below equation.

$$Amount\ fluorescein = \frac{Absorbance - 0{,}029}{3{,}0269}$$

2.3.3 Soil protein

A total of 3.00 g of dried and sieved soil was weighed into a pressure- and heat-stable glass screw-top tube, and 24.00 ml of sodium citrate buffer (20 mM, pH 7.0) was added. The mixture was shaken for 5 minutes at 180 rpm to disperse aggregates and ensure thorough mixing.

The tubes were autoclaved for 30 minutes at 121°C and 15 psi pressure and then allowed to cool. After cooling, 2 ml of the slurry was withdrawn into a smaller microcentrifuge tube and centrifuged at 10,000 x gravity to remove soil particles.

A small subsample (10µl) of this clarified extract was used in a standard colorimetric protein quantification assay (BCA) to determine the total protein content of the extract. The Thermo Pierce BCA protein assay was used, miniaturized for use in 96-well microplates, and incubated at 60°C to ensure uniform response to different protein types. Colour development was measured in a spectrophotometric plate reader (Thermo Scientific, Multiskan GO).

2.3.4 Soil organic matter

The soil samples were dried at a temperature of 105°C for two hours, to eliminate all moisture content. Subsequently, the dried sample was carefully weighed, and its initial weight was recorded.

Following the initial weighing, the sample was ashed, which involved heating it at 500°C for a duration of two hours. After this heating, the sample was once again weighed to determine the percentage of mass lost during the ignition process.

To calculate the percentage of organic matter (% OM) in the sample, the percentage of loss on ignition (% LOI) was utilized in the following formula: % OM = (% LOI * 0.7) - 0.23. This calculation allowed for the precise determination of the organic matter content within the soil sample.

2.3.5 Active carbon

A 2.5 g sample of the air-dried soil (sieved to 2mm) was carefully placed into a 50 ml centrifuge tube that was filled with 20 ml of a 0.02 M potassium permanganate ($KMnO_4$) solution, which is deep purple in colour.

The soil and $KMnO_4$ solution were shaken for exactly 2 minutes to initiate the oxidation of active carbon within the sample. As a result of this oxidation reaction, the purple colour of the solution became progressively lighter.

Subsequently, the sample tube was allowed to settle for a duration of 8 minutes before the supernatant was carefully pipetted into another tube. It was then diluted with 20 ml distilled water. To quantify the active carbon content, the absorbance of the solution was measured at a wavelength of 550 nm using a (Hach DR3900). To interpret the sample absorbance data, a calibration curve was created by measuring the absorbance of a standard dilution series of $KMnO_4$.

To convert the sample absorbance value into active carbon content, expressed in units of milligrams of carbon per kilogram of soil the formula provided in the Cornell CASH protocol (Moebius-Clune et al., 2017) was used.

2.3.6 Standard nutrient analysis

The standard nutrient analysis was performed by LMI AB (Helsingborg, Sweden) using Spurway analysis. Samples were dried, mixed, and sieved. Subsequently, conductivity and pH measurements were taken following a 15-minute soaking period in distilled water for pH and a 30-minute soaking period for conductivity. Nutrient extraction was carried out using a mild acetic acid solution over a 30-minute duration, followed by filtration. The nutrient content was quantified using spectrometry.

2.4 Soil physical parameters

2.4.1 Bulk Density

The soil bulk density was measured in-situ using an Eijkelkamp Penetrologger. In each of the three blocks of the three different sampling sites (market garden, field and natural) eight individual measurements were performed.

For the measurement, the Eijkelkamp Penetrologger was inserted vertically into the soil and downward pressure was gradually applied until it reached the maximum depth. Depth readings were automatically recorded during this process.

2.4.2 Soil Texture

Approximately 14g of the sieved soil, with a variance of +/- 0.1g, was carefully placed into a 50ml centrifuge tube containing 42ml of a dispersant solution consisting of 3% sodium hexametaphosphate, which acted as a detergent.

The tube was subjected to shaking on a reciprocating shaker for a duration of 2 hours to ensure thorough dispersion of the soil into suspension. The entire contents of the centrifuge tube were subsequently washed onto a sieve assembly, comprising a 0.053mm sieve positioned above a funnel that directed the washings into a 1L beaker. Sand particles captured on top of the sieve were collected and transferred into a pre-weighed metal can, which was set aside. The silt and clay particles that collected in the 1L beaker were resuspended through stirring and allowed to settle for 2 hours.

Following the settling period, the clay in suspension was decanted, and the settled silt was washed into a second pre-weighed can. Both cans, one containing the sand fraction and the other housing the silt fraction, were subjected to drying at 105°C until reaching a constant weight. The dry weights were recorded, and the percentages of sand, silt, and clay were calculated.

2.5 Statistical analysis

In the statistical analysis figures were created using RStudio version 4.0.5 (The R Foundation for Statistical Computing). To ascertain the statistical significance of observed variations and trends, analysis of variance (ANOVA) test was conducted, allowing for the exploration of potential differences among different groups within the dataset. Subsequently, Tukey's Honestly Significant Difference (TukeyHSD) tests were applied as post hoc analyses to perform pairwise comparisons, enabling a detailed examination of specific group differences. Notably, unless otherwise specified, calculations were carried out in Microsoft Excel following the provided instructions of the CASH protocol from Cornell University or using upon request provided workbooks.

3. Results

3.1 Systematic error

A systematic error was identified in the dataset, originating in the rockiness of the first natural sampling site. Due to the challenging terrain, only topsoil samples were obtainable for this block rather than full soil auger samples as for the other two sampling sites. Subsequent statistical analysis brought to light a consistent and notable elevation in the measured values of the first natural block compared to the broader dataset (the market garden and the field system) and even in comparison to the other blocks within the natural system (Figure 5).

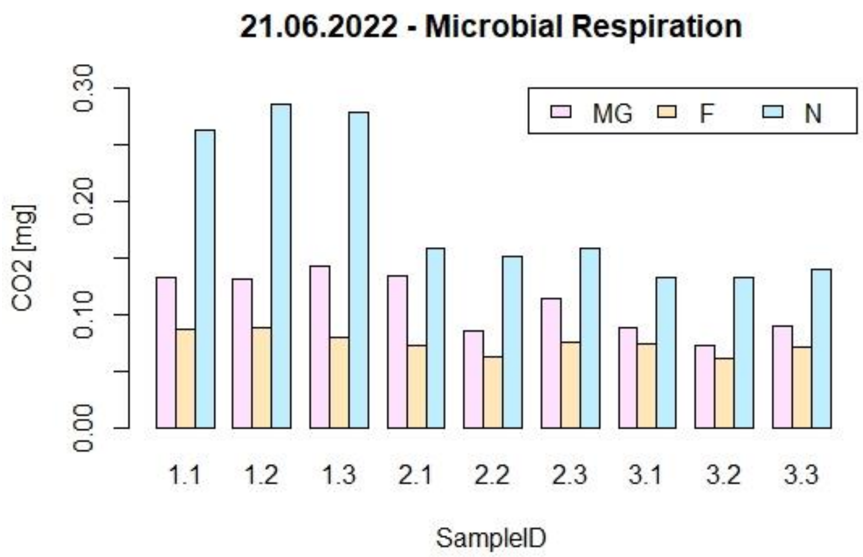


Figure 5: An exemplary dataset (microbial respiration) for the natural system (blue) in comparison to the market garden system (pink) and the field (yellow). The values of the first sample (1.1, 1.2, 1.3) are significantly higher than the rest of the samples and therefore were excluded from the dataset as systematic error to maintain statistical comparability.

Recognizing the potential distortion introduced by this localized discrepancy, the decision was made to exclude these values from further analysis to ensure statistical comparability across the dataset (Figure 6). This strategic omission aims to mitigate the influence of the identified systematic error for all affected parameters, maintaining the integrity and reliability of the overall statistical outcomes.

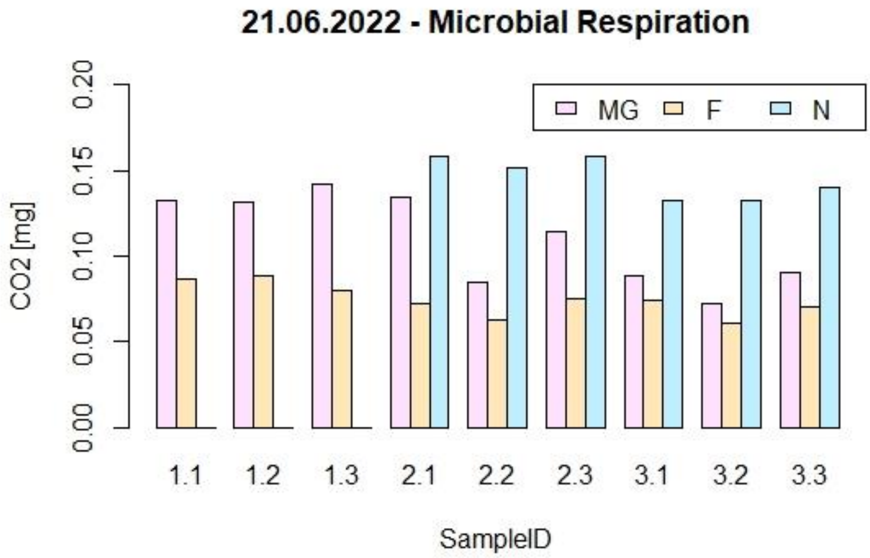


Figure 6: Display of the altered exemplary microbial respiration data set. Notably the first three samples, block 1, in the natural system has been removed (samples 1.1 – 1.3). This procedure has been performed throughout the data sets of all affected parameters.

3.2 Microbial Respiration

The initial sampling of the market gardening system took place about two months after the compost treatment. The measured microbial respiration in June 2022 resulted in the highest CO_2 values in comparison to the consecutive samplings (Figure 7). Thus, microbial respiration values declined over the course of the sampling period 2022 – 2023, with significant differences seen between the first and the subsequent sampling ($p = 0.006$), as well as the first and the final sampling ($p = 0.001$).

The results of the field system showed a reoccurring trend: the early season samples yielding in significantly greater microbial respiration values in comparison to the later season samples ($p \leq 0.04$). Comparison of the CO_2 levels in the initial and the final state of the field system showed a significant decline of microbial respiration ($p = 0.0$) between the years 2022 and 2023.

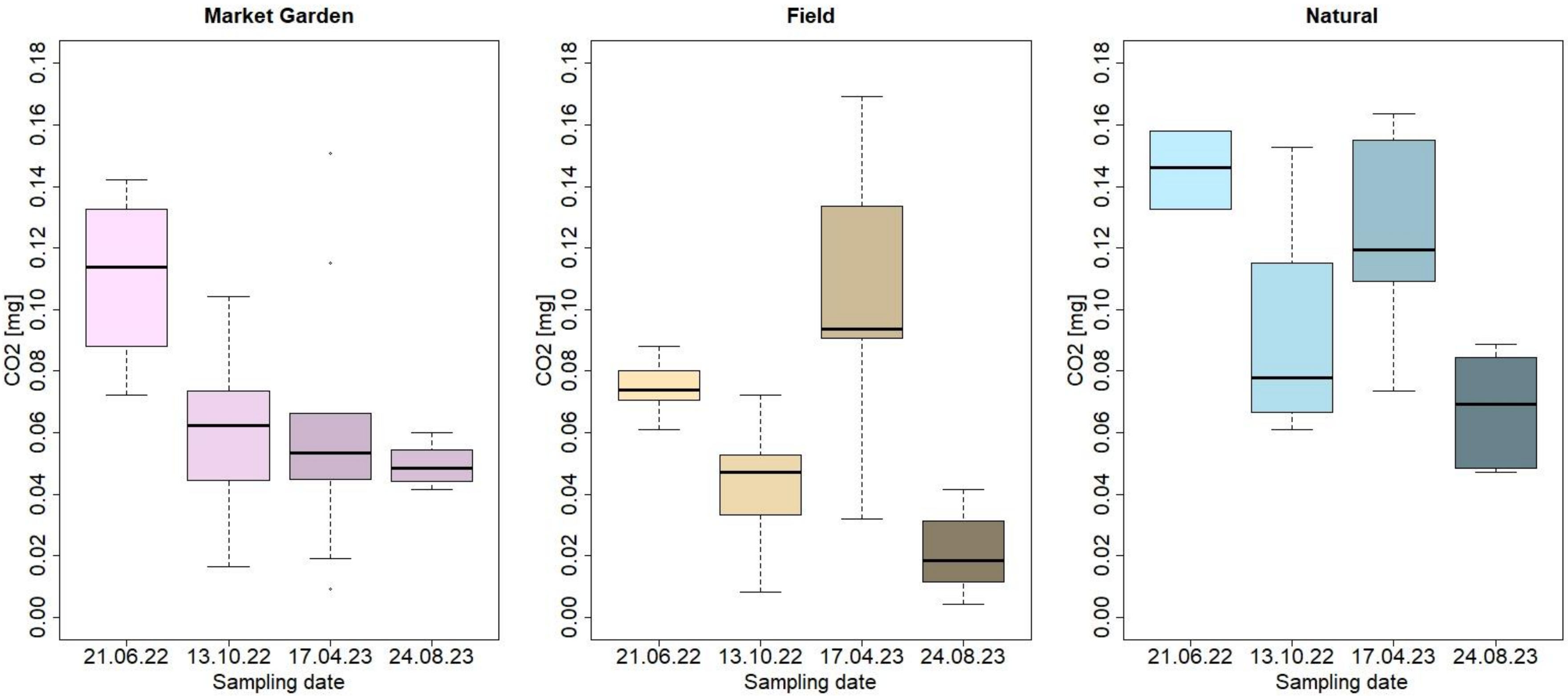


Figure 7 displays the microbial respiration results of the three different management systems: organic market gardening (MG, pink), organic conventional agriculture (F, yellow) and unmanaged natural fence line (N, blue). Samples were obtained with a soil auger (0-40cm depth) during the research period 2022 -2023. Microbial respiration values were the result of an incubation analysis and are displayed in mg CO_2.

In the natural system, like the market gardening system, the results of the first sampling (21.06.2022) had the highest microbial respiration values, compared to the later samplings (Figure 7). Additionally, a similar significant trend of greater respiration values in the early season compared to the late season samplings was observed ($p = 0.01$ and 0.002 respectively). Finally, respiration values of 20.06.22 were significantly higher than the values of 24.08.23 in the natural system ($p = 0.000$), also indicating a decline in microbial respiration throughout the study period.

Comparison between the systems (separated by sampling date) resulted in high statistical significance between all systems ($p < 0.003$), with the MG system presenting higher CO_2 values than the F system, but smaller values than the N system (Figure 7). The final system state comparison suggests that the market garden management has successfully increased, and stabilized, the microbial respiration in comparison to the present management in the field system ($p = 0.000$).

3.3 Fluorescein diacetate (FDA) hydrolysis assay

The FDA values of the market gardening system repeated the trends observed in the microbial respiration: (1) the highest FDA values were obtained in the first sampling period, (2) the early season samples yielded in higher FDA values compared to the late season samples ($p = 0.0$ and 0.22), (3) FDA values declined significantly over the research period, resulting in a (4) significant final to initial state difference of $p = 0.01$ (Figure 8).

In the field system, no statistically significant differences were obtained amongst the sampling dates ($p \geq 0.089$). Thus, the microbial activity measured in the field system over the period of 2022 – 2023 was not impacted by the presented management.

Comparing the FDA results of the first sampling date in the natural system with the consecutive sampling occasions only results in statistical significance with the last sampling date ($p = 0.014$). Thus, the sampling date 24.08.2023 shows much lower measurable FDA values presenting a statistically significant decrease of microbial activity since the beginning of the research.

In the first and the third sampling date of the internal comparisons, the market garden system presented higher FDA values than the field system ($p \leq 0.017$) as well as the natural system ($p \leq 0.004$). The final state comparison confirms the trend (Figure 8), yet without statistical significance ($p = 0.072$).

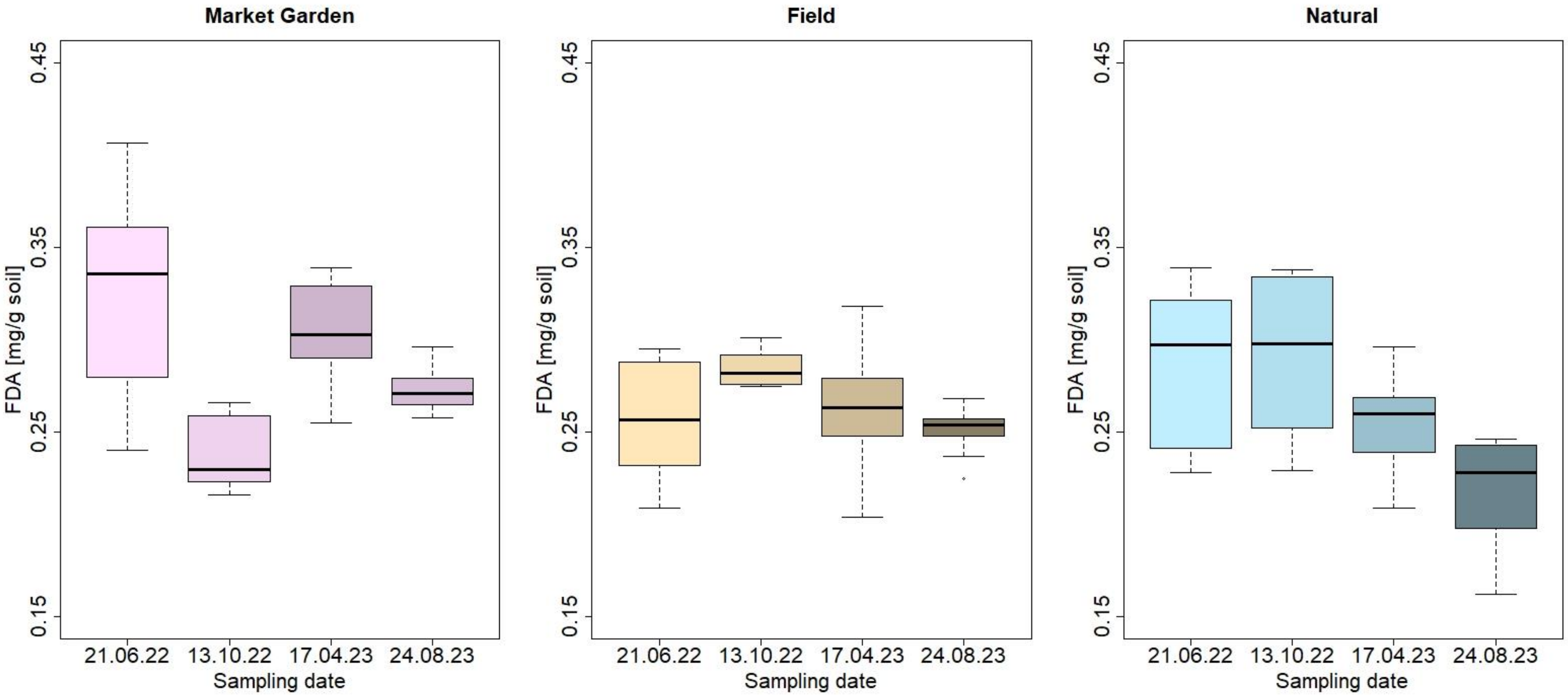


Figure 8: Presentation of the FDA results (mg/g soil), obtained from the three different research systems included in the correlation assessment of management practices and biological soil health. In the market gardening system (pink) the management comprises of no-dig biointensive production principles, while the field system (yellow) is a machine managed organic agricultural production. The unmanaged fence line serves as a representative of a potential natural state (blue). Soil samples were taken in all three systems at four different sampling time points.

3.4 Soil protein

In comparing the first three samplings of the MG system, no significant difference was observed ($p \geq 0.306$). However, on August 24, 2023, a notable increase was seen, indicating a significant rise of soil protein content compared to the previous samples ($p \leq 0.003$). Accordingly, the protein content of the last sampling is significantly higher than the first sampling ($p = 0.016$), suggesting successful management impact in the market gardening system over the research period.

For the field system, protein values indicated a low but steady soil protein content throughout 2022 – 2023, with no significant differences observed between sampling dates (p-values > 0.428).

In the natural system, the first sampling presented the highest soil protein values (Figure 9). Thus, significant difference was found when comparing the first sampling with consecutive samples ($p \leq 0.026$), indicating a significant decline in soil protein content across the natural system.

In the results of the first sampling period on June 21, 2022, no significant difference was found between the MG system and the N system ($p = 0.985$). Thus, the management strategy in the MG system elevated the soil protein content from significantly lower levels observed in the field system ($p = 0.0$) to natural levels in the beginning of the 2022 season (Figure 9). For the rest of the sampling period 2022 – 2023, a repeated trend with statistical significance was observed: the market gardening system yielded soil protein results significantly higher than those present in the other systems ($p \leq 0.018$). Therefore, it can be assumed that the treatment of the market gardening system not only managed to stabilize the protein levels present in the soil over the course of the research period but also increased them about twofold in comparison to the field as well as the natural system. Additionally, the significant difference between the natural system and the field system in 2022 ($p \leq 0.01$) changed to differences without significance ($p \geq 0.211$), indicating potential impact of external factors active outside the market gardening system.

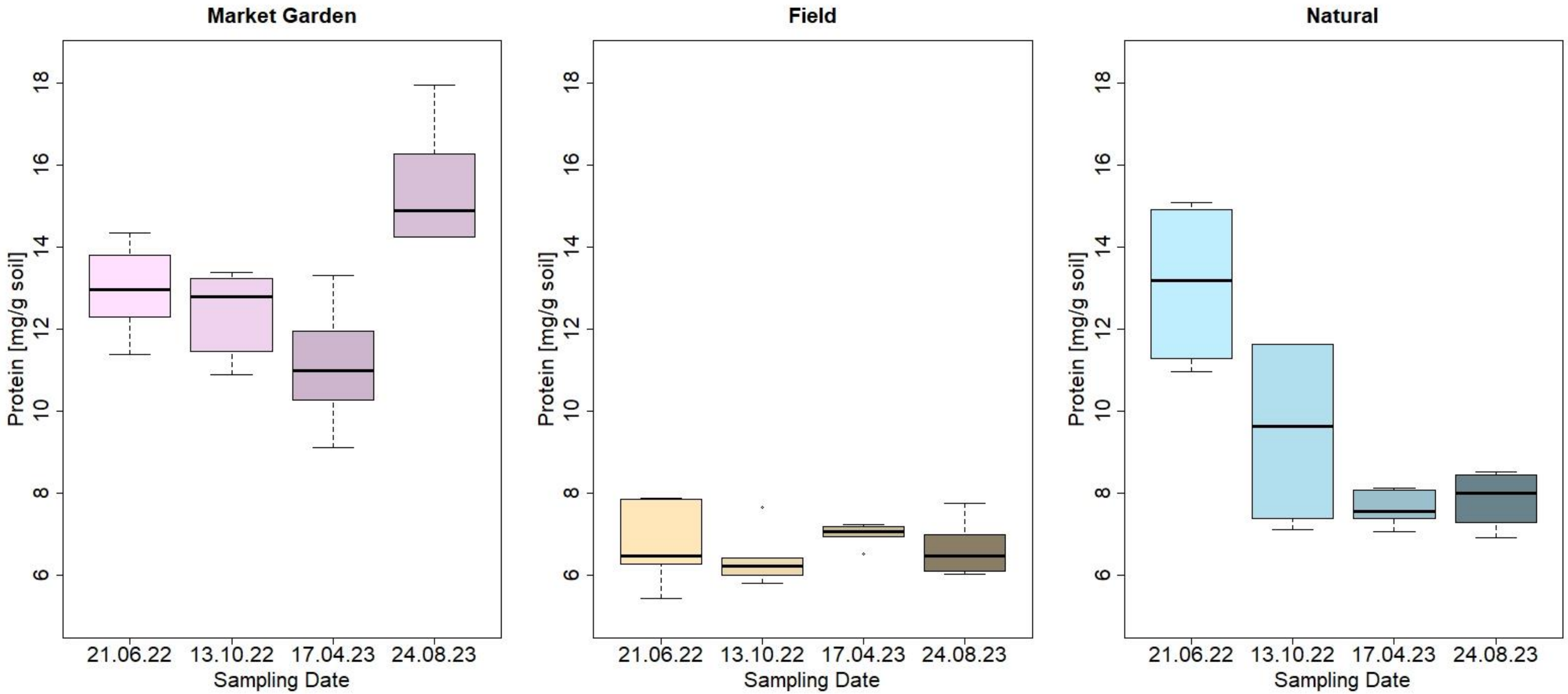


Figure 9 presents the soil protein values (mg/g soil) measured in a standard colorimetric protein quantification assay as part of the biological soil health research project 2022 -2023. Samples originate from three different management systems ins Skåne, Southern Sweden: (1) organic market gardening (pink), an organically managed agricultural production (yellow) and an unmanaged tree fence line (blue) as a natural reference. During the research period, soil samples were taken at four different sampling dates, covering a soil depth of 0-40 cm.

3.5 Soil organic matter (SOM)

Comparison of the first three MG samples did not yield any differences ($p \geq 0.847$), indicating a stable organic matter content in the first 10 months of the MG system. However, the organic matter levels measured in the last sampling date (24.08.23) increased significantly in comparison to all previous samples ($p \leq 0.011$).

Organic matter percentages in the field system remained stable across sampling dates (p – values ≥ 0.45), with no significant results. Seasonal patterns were not observed.

The natural system exhibited a decline in organic matter over the research period. The second sampling date (13.10.22) showed a significant decrease ($p = 0.010$) compared to the first date (20.06.22). The last two samplings in 2023 maintained lowered levels, with no significant difference ($p = 0.984$). A significant decrease in organic matter was observed over the course of the research period ($p = 0.01$)

Comparing systems within each sampling date revealed no significant difference between MG and N in the first sampling ($p = 0.327$). However, both had significantly higher OM levels than the field system ($p = 0.0$). Subsequent samplings showed significant differences between all systems (p = ≤ 0.035). The market gardening system consistently presented the highest OM values, surpassing the natural and field systems (Figure 10). Thus, the management applied to the MG system successfully increased and stabilized OM levels, exceeding naturally occurring OM levels. The resulting organic matter levels in the market garden system were 50% higher than those in the natural system and more than 100% higher than those in the field system.

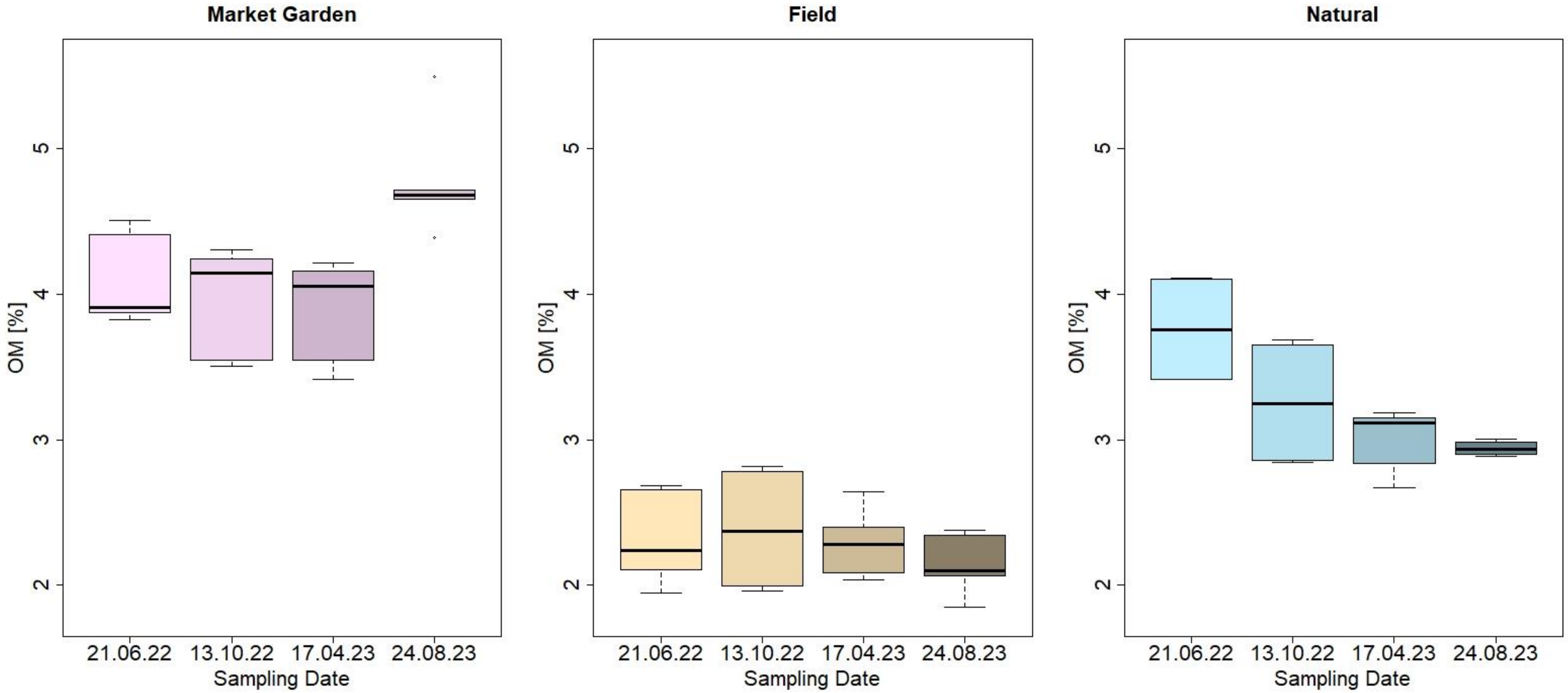


Figure 10: Individual display of organic matter results (loss on ignition) for the research systems organic market garden (pink), organic agricultural field (yellow) and natural fence line (blue).Samples were taken at four different occasions during 2022 – 2023. Sampling was executed with a soil auger to a depth of 40cm.

3.6 Active carbon

Due to the large active carbon value range in the market gardening system on 13.10.22 no significant differences were identified in the research period 2022-2023 ($p \geq 0.266$). Nevertheless, an insignificant stabilization and increase of active carbon levels present in the soil under market gardening management was noted when comparing the initial with the final state of the system ($p = 0.37$).

The first sampling in the field system in June 2022 resulted in the lowest active carbon values of the research period. Significant increases were observed in subsequent samplings ($p \leq 0.047$), thus indicating the management's impact on active carbon levels present during 2022 - 2023.

A reverse development was observed in the natural fence line bordering the market gardening and the field system. Highest active carbon values were measured in the first sampling in June 2022 (Figure 11). A significant decline occurred by the next sampling on 13.10.22 ($p = 0.001$). In 2023, values partly recovered and stabilized showing no statistical significance when compared ($p = 0.358$) but when compared to the initial sampling in 2022, an insignificant decrease in active carbon levels during the 2022–2023 sampling period was measured ($p = 0.161$).

Comparing system results within the sampling date presented the same trend as seen in previous parameters: in the first sampling 2022 the N and the MG system both had significantly higher active carbon levels than the field system ($p = 0.0$). In the subsequent sampling and throughout the sampling period, the MG system presented the highest active carbon values. Significant difference was seen between the market garden and the field in the first ($p = 0.0$) and the last sampling ($p = 0.0$) while no difference could be measured between the MG and the N at this sampling time. Accordingly, the market gardening management increased the active carbon levels similar to values present in natural systems during the research period (Figure 11).

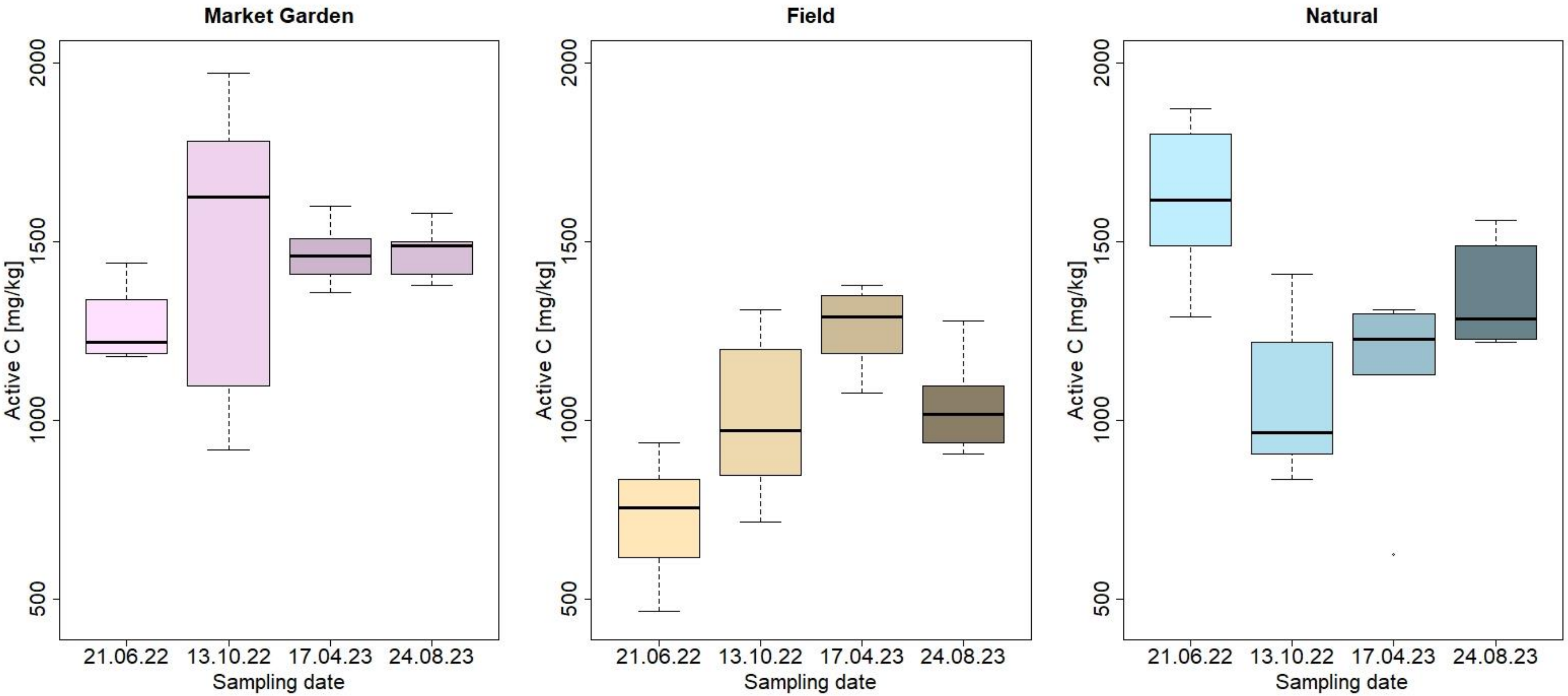


Figure 11 presents the active carbon levels obtained during the research project ''Enhancing Biological Soil Health through Land-management Change'' carried out in 2022 -2023. Research subjects were an organically managed market gardening system (pink), in comparison to an organically managed agricultural production (yellow) and an unmanaged fence line as natural reference (blue). During the research period four soil samplings were performed (0-40cm depth), providing insight into the systems biological soil health status and development.

3.7 Standard nutrient analysis

Due to limited soil volumes in the natural system at the first sampling occasion, only one sample (instead of three) was subjected to standard nutrient analysis. Thus, statistical analysis did not yield any results when comparing the different samplings in the natural system.

3.7.1 pH

The measured pH values compared within the individual systems did not show significant differences ($p \geq 0.205$). Nevertheless, significant differences occurred when comparing the MG as well as N system with the field system ($p \leq 0.005$), while no difference was found between the MG and N system ($p \geq 0.087$). Accordingly, the market gardening management increased and stabilized the pH values over the course of the research period in a value range measurable in the natural reference system (Figure 12).

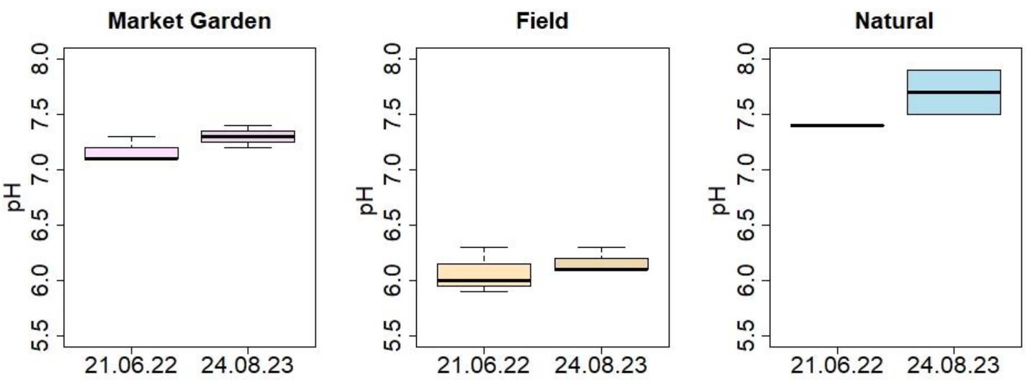


Figure 12: displays the initial to final state comparison results for the pH values measured in the market gardening system (pink), the field production (yellow) and the natural reference system, an unmanaged fence line (blue). Soil samples were taken between zero and 40 cm.

3.7.2 Available Nitrogen (Nmin)

Available nitrogen (Nmin) levels represent the fraction of nitrogen in the soil which is available for plant uptake. The results obtained from samplings in the research systems (MG, F and N) suggest a significant decline of Nmin during the research period in the field and natural system ($p \leq 0.001$). At the first sampling in June 2022, the market gardening system presented significantly higher results of available nitrogen than the other systems ($p \leq 0.031$). This trend continued until the end of the research period but without statistical significance in the final system comparison ($p \leq 0.11$). Still, at the final sampling in August 2023, the plant available nitrogen was twofold higher in the MG compared to the F and N system (Figure 13).

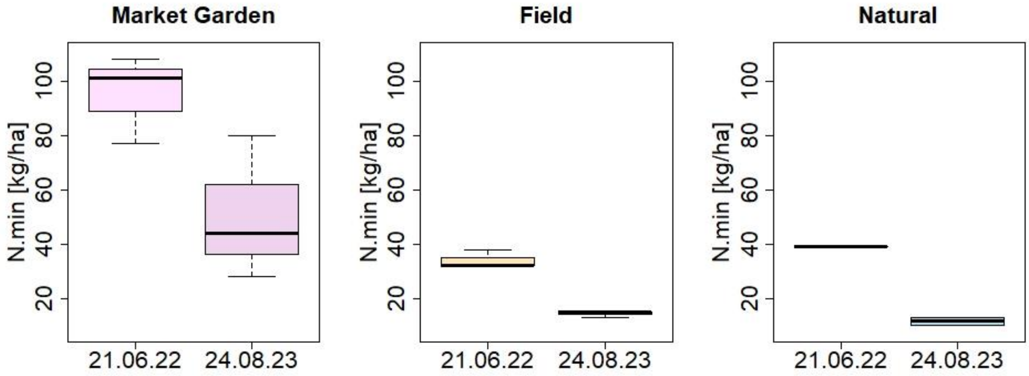


Figure 13: The final state comparison results for the plant available nitrogen present in the research systems (market gardening = pink, field = yellow and natural = blue) during the sampling period 2022 – 2023. Soil samples were taken to a depth of 40 cm with a soil auger and analysed by LMI AB (Helsingborg, Sweden).

3.7.3 Phosphorus

Phosphorus levels observed in the market gardening system were significantly higher (Figure 45) compared to the other systems (F and N) at the initial state of the research project as well as at the final sampling point ($p \leq 0.019$). Even though the phosphorous levels increased significantly during the research period in the field system ($p = 0.047$).

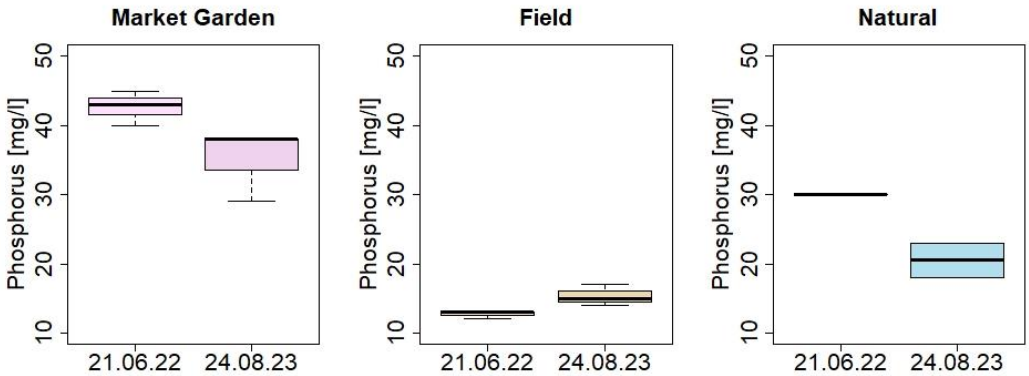


Figure 14: Presentation of the phosphorus results measured during the research period 2022 – 2023 in the three research systems: organic market gardening (pink), organic agriculture (yellow) and a natural fence line (blue) as a proxy of unmanaged soil conditions. Soil was sampled down to 40cm depths and analysed applying a standard Spurway analysis.

3.7.4 Potassium

While there was a significant decline of potassium on the market garden comparing the initial and the final sampling values ($p = 0.003$), the values in the other research systems maintained stabile ($p \geq 0.101$). Nevertheless, potassium levels measured in the market gardening system were significantly higher than the levels present in the field and the natural system ($p \leq 0.014$) during the research period 2022 – 2023 (Figure 15).

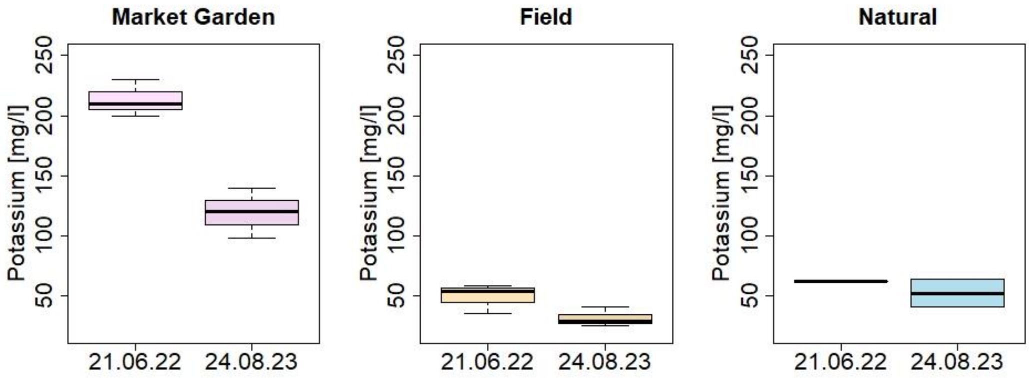


Figure 15: displays the measured potassium levels in the research project "Enhancing Biological Soil Health through Land-management Change" carried out in 2022 -2023. Research subjects were an organically managed market gardening system (pink), an organically managed agricultural production (yellow) and an unmanaged fence line (blue). During the research period four soil samplings were taken (0-40cm depth) using a soil auger.

3.8 Bulk Density

In-situ bulk density measured in the market gardening system (soil profile: 0-65cm depth) was significantly lower compared to the bulk density values measured in the field system at the same depth ($p \leq 0.005$). In the field system, bulk density increased with depths, showing a maximum at a depth between 35 and 40 cm (Figure 16), followed by a density decline in the further profile (depth 40 – 75 cm). Maximum soil density levels (≥ 4 MPa) at around 35 cm depth in an agricultural production could indicate the presence of a plough pan (Burgos Hernández et al., 2019). A similar density distribution was observed in the profile of the market gardening system, showing peak values at 40 – 45 cm depth and a density decrease in the lower profile. The offset of maximum values in the MG system could be due to the management impact of the broad fork (40cm). No difference could be measured comparing the penetration profiles of field system with the natural system ($p \geq 0.295$). Due to rocky soil conditions and high soil strength, soil penetration further than 40 cm depth was not possible in the natural fence line, in fact most samples only reached down to 15 – 20 cm.

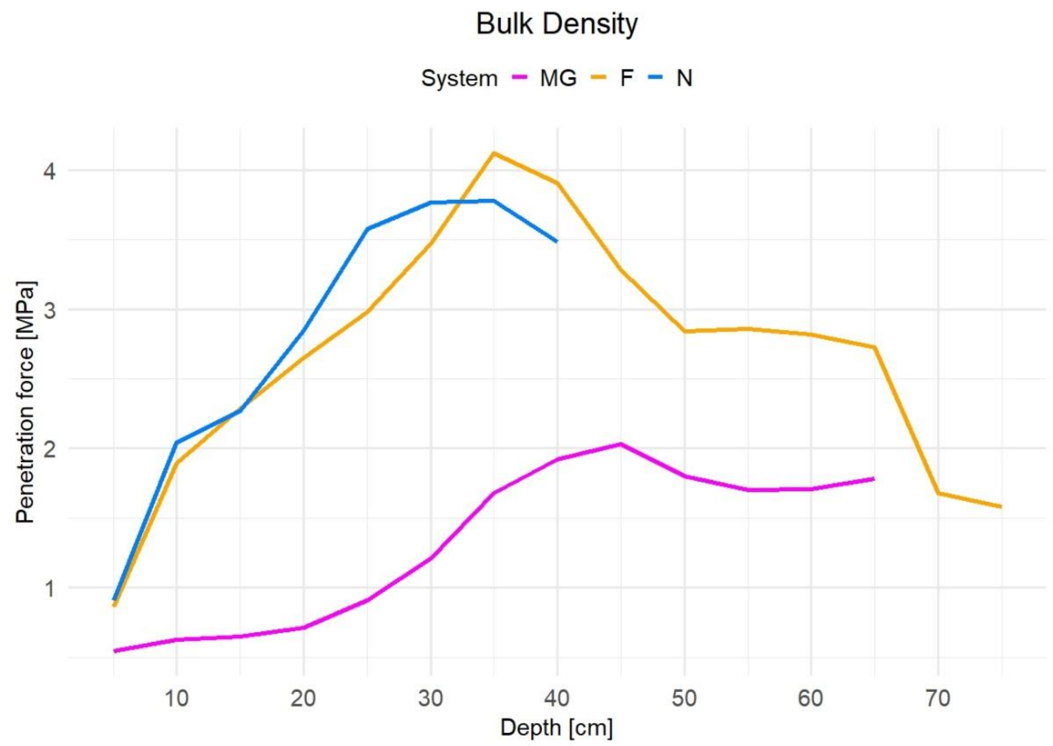


Figure 16 presents the measured bulk density profiles of the three research systems: organic market garden (pink), organic agriculture (blue) and the natural reference represented by an unmanaged fence line (blue). Soil bulk density was measured in-situ using an Eijkelkamp Penetrologger down to 65 – 75 cm in the market garden and the field system respectively. Due to rocky soil conditions measurements could only reach a maximum depth of 40 cm in the natural system.

3.9 Soil Texture

The relative amounts (%) of the components sand, silt and clay measured in the market gardening system in 2022 resulted in the classification of the soil as a “sandy loam” using the soil classification triangle provided by Zyserman et al. (2017) (Figure 19, Appendix 1). Changes in the soil component distribution over the research period did not lead to a change of soil classification in the market gardening system (Figure 17). The soil obtained in 2022 from the field system was classified as on the boarder of “sandy loam” to “loamy sand” with a slight tendency towards the “sandy loam”. The tendency had changed in the final sampling of the field system in 2023 resulting in a soil classification as a “loamy sand”. The relative amount of the soil components in the natural system showed only minor changes, thus the soil was classified as a “sandy loam” for the initial as well as the final system sampling in the research period 2022 -2023 (Figure 17).

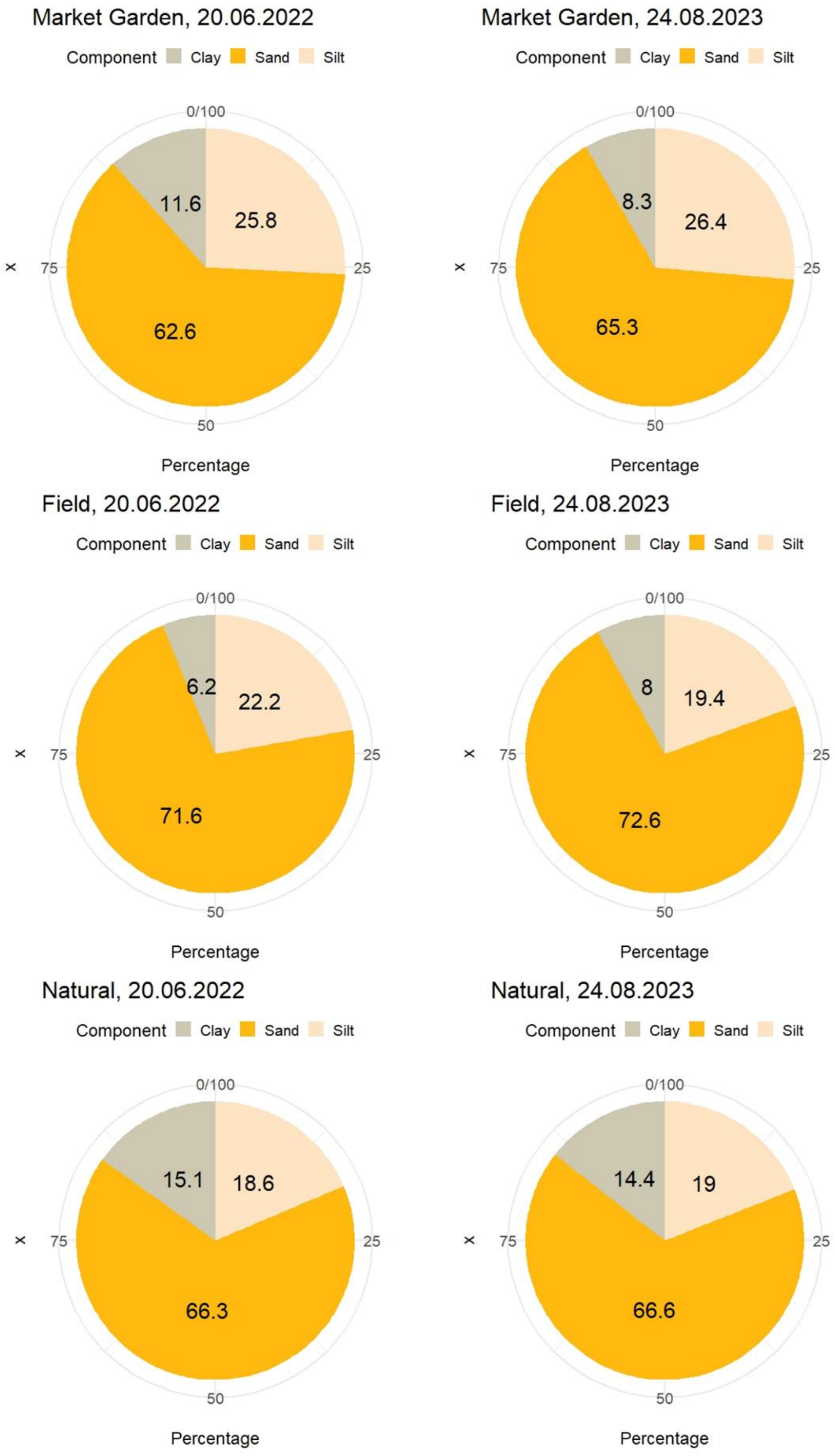


Figure 17: Soil texture development in the research systems market garden (top), the field system (centre) and the natural fence line (bottom). The displayed pie charts are separated in the percentage amounts of the main soil components sand (yellow), silt (beige) and clay (grey).The left side of the figure displays the soil texture results obtained in 2022, while the right sight shows the results from the final sampling. Soil samples were taken with a soil auger (40 cm).

4. Discussion

4.1 Market gardening and biological soil health

Conventional food production systems are facing simultaneous challenges: (1) an increase in food demand due to a growing global population (EU, 2023), (2) soil fertility depletion due to a negative impact of conventional farming on agroecosystem health (Rillig et al., 2019), and the current (3) climate crisis creating higher instability in production conditions (Stern, 2016). Ergo, the status quo in farming is not applicable to maintain future food security (Tilman et al., 2001). Thus, to create independence of unsustainable production methods, alternatives providing environmentally, socially, and economically just farming systems focussing on reversing soil fertility depletion and poor soil health conditions are urgently needed (McLennon et al., 2021, Tilman et al., 2002).

Biointensive market gardening is characterized by an agroecological approach to small-scale, intensive farming, which emphasizes on social, financial, and ecological sustainability (Tittonell, 2014). Small-scale market gardens primarily depend on human labour and usually utilize farmers markets or community supported agriculture (CSA) schemes to directly market their harvest to consumers (Drottberger et al., 2021). Rooted in the principles of diversified farming, this method aims to maximize yields while minimizing inputs and environmental impact (Altieri and Nicholls, 2004). Key principles include no-dig soil aeration, composting for mulching, and crop diversity to encourage biodiversity (Fortier et al., 2014).

In accordance with Rosberg and Alsanius (2022) and Barreiro et al. (2022), this research was carried out to explore the impact of land use management change on biological soil health parameters, applying organic market gardening management on previous agricultural land, in comparison to an organic conventional production and a natural reference system.

The biological soil health parameters in the newly established market gardening system (established on the same soil as the conventional organic production: field system), responded positively to the biointensive management practices. As hypothesized, the parameters soil organic matter (SOM), soil protein, bulk density, and the measured plant available nutrients (N.min, P and K) in the MG system showed significantly increased values in comparison to the F system.

The application of organic amendments in combination with a no-dig management increased SOM levels in the market gardening system by 123% compared to the conventional field system (Figure 10). According to Rahman et al. (2021) and Song et al. (2019), elevated SOM levels serve as a carbon sink which enhances nutrient cycling, soil structure formation, and water retention, while supporting plant and microbial communities. In the first production year, the market gardening management exceeded the expected SOM increase of 11 – 49% typical for a large-scale conservation agriculture (CA) management reported by Perego et al. (2019) as well as the long-term effect of up to 94% SOM increase reported in a long-term experiment (10 years) conducted by Roy et al. (2022). Hepperly et al. (2018) emphasise the importance of building SOM in agricultural soils to break the green revolution paradigm of fertilizer dependency as the global nutritional solution. Accordingly, Davis et al. (2023) reported soils rich in SOM exhibit reduced dependency on agricultural inputs and according to Moebius-Clune et al. (2017) increased resilience to drought or intense precipitation events. Confirming the hypothesis, market gardening promotes ecosystem functionality as well as increases the agroecosystems adaptive capacity to confront global warming.

Soil protein content serves as a reservoir of organically bound nitrogen (Norg) within the soil organic matter (SOM), subject to potential mineralization through microbial processes, providing an accessible nitrogen source for plant absorption (Moebius-Clune et al., 2017). A large proportion of soil proteins are synthesized by arbuscular mycorrhizal fungi and play an important role in the formation of water-stable aggregates relevant for water storage as well as movement (Barreiro et al., 2022). According to Liu et al. (2020) fungal soil proteins contribute to SOM and soil nitrogen accumulation, accounting for up to 5% of soil C and 3% of N respectively, which exceeds the contribution of soil microbial biomass.

Bulk density decrease, as indicated by penetration resistance, represents the increase in soil porosity essential for water, air, root, and microbial movement within the soil matrix (Moebius-Clune et al., 2017). According to Burgos Hernández et al. (2019), the measured bulk density readings above 2 MPa (30 – 40 cm depth) in the field system (Figure 16), indicate the presence of a plough pan. Aligning with the results of Lehmann et al. (2020a), Liu et al. (2020), Liu et al. (2019), Zhu et al. (2019) and Sekaran et al. (2021) bulk density measurements in the MG system were significantly lower than the density values in the neighbouring F system due to CA like no-dig management, especially in the plough pan prone soil depth (Figure 16). Accordingly, the no-dig market gardening management not only resulted in overall decreased bulk density, but consequently successfully reversed the presence of an established plough pan. Page et al. (2020) link decreased bulk density with increased soil water retention due to continuity of soil pores, and improved habitat conditions for crops as well as microorganisms.

To reduce the loss of fungal activity and soil structure caused by consecutive tillage practices, Lehmann et al. (2020a) and Rillig et al. (2019) emphasized the importance of no-till management practices to protect the arbuscular mycorrhizal symbiosis to reach long-term sustainability in food production.

The availability of nutrients plays an important role in crop health and yield optimization, especially since among the eighteen essential elements required by plants, nitrogen, phosphorus (P), and potassium (K) frequently exhibit deficiencies in soil environments (Moebius-Clune et al., 2017). The observed increase in Nmin within the market gardening system could be attributed to the liquid fertilization management. Alternatively, authors like Almagro et al. (2023), Lehmann et al. (2020a) and Sekaran et al. (2021) suggest the measured Nmin increase, due to conservation agricultural management (less soil disturbance), stems from elevated fungal content within the soil ecosystem. Consequently, the assumed increased fungal presence could correlate with increased soil protein concentrations and subsequently lead to enhanced storage as well as availability of nitrogen in the market gardening system (Liu et al., 2019). P is an essential macronutrient important for plant development, thus a scarcity of soil P can impact all plant development stages (Stribley et al., 1980). In the final stage comparison, the increase of 116% and 250% for P and K respectively, aligns with the findings of Nguyen et al. (2019) reporting the capability of CA to increase essential nutrient levels in soils. On the other hand, the increase could correlate with the high amount of organic compost imported into the MG system (Appendix 1, Figure 20 – 22).

The microbial activity parameters (microbial respiration, FDA, and active carbon) confirm the trend observed in the previous parameters, and thus the research hypothesis, however less pronounced. The MG system still resulted in significantly higher final values compared to the F system, but ranged around similar values as measured in the N system.

According to Daverkosen et al. (2022), Moebius-Clune et al. (2017), Sekaran et al. (2020), the combination of respiration metrics and FDA values measures the functionality of soil microbial communities: the capacity to degrade, assimilate and metabolize organic residues, modulate carbon sequestration dynamics, facilitate nutrient mineralization, regulate nutrient storage, cycling as well as availability, and the development of optimal soil structure – processes essential for long term agroecosystem resilience (Tilman et al., 2002).

Active carbon represents the supply of available food and energy sources for the soil microbial community (Bongiorno et al., 2019) and thus correlates with microbial respiration and biomass (Lal, 2016). According to Huber et al. (2023), active carbon responds quickly to alterations in crop and soil management practices, hence monitoring active carbon levels can help understand the short-term impact of management adjustments in the production system.

The compost added in the market gardening treatment originated form municipal green waste compost (Sysav, Malmö). Soil microbial communities generally have a C:N ratio between 4 – 8:1 (Bhogal et al., 2018). According Soong et al. (2020) and Yang et al. (2020), carbon resources with a high C:N ratio (> 20:1) limit microbial growth due to N immobilization. Decomposition processes above the C:N threshold of 20:1 are dominated by saprophytic fungal activity (Liang et al., 2017). Accordingly, the N limitation in the C rich compost treatment (C:N ~ 16:1, Appendix 1, Figure 20 – 22) could serve as an explanation for the restrained increase of microbial activity (Figure 7 & Figure 8) in the MG system. Following the above narrative supported by Bhogal et al. (2018), Brock et al. (2021), Bongiorno et al. (2019), Lucas and Weil (2021) and Daverkosen et al. (2022), the complexity of the chosen organic amendment might have caused a shift towards a fungal dominated microbiome, indicating a potential dependency of the soil bacteria on fungal activities for the provision of available active carbon. Thus, changes in soil biological and physical functioning appear to correlate with the quality of the organic matter (Bhogal et al., 2018, Daverkosen et al., 2022). Nevertheless, the impact of SOM in the MG system significantly increased microbial activity compared to the F system, confirming the research hypothesis.

Due to optimized soil and agroecosystem functioning, increased management and production efficacy, higher levels of productivity per square meter in comparison to conventional farming operations can be assumed (Page et al., 2020). Consequently, small-scale farming practices, when managed carefully, could mitigate environmental degradation, and contribute to localized food security, while aligning with the United Nations' Sustainable Development Goals (Alsanius et al., 2023, Pépin et al., 2021). The holistic approach contributes to the SDG 2, 3, 12 and 13, which emphasize zero hunger, good health and well-being, sustainable food production and consumption patterns, as well as climate change mitigation., thereby reinforcing its role in advancing global sustainability agendas.

4.2 Methodological considerations

Climatic variations, irrigation practices, and cover crop dynamics were identified as potential external impacts shaping soil microbial activities and overall system functionality (Rosberg and Alsanius, 2022). Notably, the observed trends indicate elevated values in 2022 across the parameters, which can be attributed to the higher precipitation during the year 2023 (Figure 5). The climatic conditions in 2023, characterized by more frequent rainfall might have resulted waterlogged soil conditions, compromising microbial activity. This observation indicates considerations for future sampling protocols tailored to consistent temperature as well as soil moisture regimes. Additionally, future timing of soil sampling needs to consider comparable time periods passed since the previous compost treatment in the market gardening system. In the present experimental setup, the initial sampling was conducted promptly after the compost treatment to monitor the immediate effects of the intervention, however subsequent samplings rather displayed the seasonal influence of colder temperatures than the impact of the compost treatment. The final sampling, impacted by the prevailing season, primarily served as an indicator of the long-term effects of the compost intervention. Moving forward, a standardized sampling schedule is needed, strategically designed to disentangle the interaction of seasonal variations from treatment-induced impacts.

4.3 Future research

Market gardening holds the potential to significantly impact the soil microbiome. Thus, soil microbial and fungal community developments and the broader implications for human and environmental health could be subjects of future research in sustainable agriculture. Central to these objectives is the exploration of microbial community shifts and the stabilization of soil health parameters. Additionally, the quality of the compost has impacted the microbial community, thus future studies investigating the correlation between carbon sources and microbiome responses are needed. Based on Montgomery et al. (2022) and Alsanius et al. (2023), the impacts of soil health on plant vitality, and thus human well-being, present opportunities for future interdisciplinary research. Exploring the connections between soil management, food quality, agroecosystem resilience and human health could support the much-needed paradigm shift towards a holistic health-centric food production.

Respectively, the transformative potential of market gardening extends beyond agricultural productivity, including the provision of non-commercial ecosystem services like climate change mitigation and community well-being (Drottberger et al., 2021). Recognizing non-commercial benefits is essential for shaping future policy frameworks (Boulestreau et al., 2023, Tittonell, 2019). These frameworks should advocate policy interventions that ensure the financial sustainability of small-scale agricultural practices based on agroecological principles (Lal, 2015). Collectively, these research objectives promote a future-oriented production paradigm, envisaging holistic food security solutions based on viable agricultural practices, resilient ecosystems, and integrative policy frameworks, aligned with global sustainability goals and the interests of our future society.

5. Conclusion

To conclude, market gardening management holds the potential to catalyse a soil health improving cascade of interconnected soil health indicators: (1) elevated soil organic matter levels (2) lead to increased microbial and fungal activity, (3) enhancing soil protein concentrations, contributing to (4) the formation of macroaggregates, facilitating (5) carbon sequestration, improving (6) soil porosity, (7) soil water conditions and (8) nutrient plant-availability. Thus, enhanced soil health correlates with (9) increased biotic and abiotic stress resilience, reinforcing the multifaceted benefits of optimal soil management practices. Despite the short research period, the presented market gardening management outcompeted the positive impact of long-term CA management in the first year of the production. Input dependency shifted from machine management and synthetic amendments to human labour and organic green waste compost. Accordingly, it can be concluded, that biointensive market gardening is a fast and viable farming method to reclaim soil health and future localized food security. Moreover, the approach aligns with various United Nations Sustainable Development Goals, including zero hunger, good health and well-being, responsible consumption, and production, as well as climate action, contributing to global sustainability agendas. Overall, biointensive market gardening emerges as a promising model for renewable and resilient agriculture in the face of evolving challenges in food production system.

References

ALMAGRO, M., DÍAZ-PEREIRA, E., BOIX-FAYOS, C., ZORNOZA, R., SÁNCHEZ-NAVARRO, V., RE, P., FERNÁNDEZ, C. & MARTÍNEZ-MENA, M. 2023. The combination of crop diversification and no tillage enhances key soil quality parameters related to soil functioning without compromising crop yields in a low-input rainfed almond orchard under semiarid Mediterranean conditions. *Agriculture, Ecosystems and Environment,* 345.

ALSANIUS, B. W., KHALIL, S., KARLSSON, M., HELLSTRÖM, M., VENDRAME, M. & ROSBERG, A. K. 2023. The two sides of the coin: sustainability and controlled environment horticulture. *Acta Horticulturae***,** 427-438.

ALTIERI, M. A. & NICHOLLS, C. I. 2004. An agroecological basis for designing diversified cropping systems in the tropics. *Journal of Crop Improvement,* 11**,** 81-103.

BARREIRO, A., FOX, A., JONGEN, M., MELO, J., MUSYOKI, M., VIEIRA, A., ZIMMERMANN, J., CARLSSON, G., CRUZ, C., LÜSCHER, A., RASCHE, F., SILVA, L., WIDMER, F. & DIMITROVA MÅRTENSSON, L. M. 2022. Soil bacteria respond to regional edapho-climatic conditions while soil fungi respond to management intensity in grasslands along a European transect. *Applied Soil Ecology,* 170.

BEHNKE, G. D., KIM, N., ZABALOY, M. C., RIGGINS, C. W., RODRIGUEZ-ZAS, S. & VILLAMIL, M. B. 2021. Soil Microbial Indicators within Rotations and Tillage Systems. *Microorganisms,* 9.

BHOGAL, A., NICHOLSON, F. A., ROLLETT, A., TAYLOR, M., LITTERICK, A., WHITTINGHAM, M. J. & WILLIAMS, J. R. 2018. Improvements in the Quality of Agricultural Soils Following Organic Material Additions Depend on Both the Quantity and Quality of the Materials Applied. *Frontiers in Sustainable Food Systems,* 2.

BONGIORNO, G., BÜNEMANN, E. K., OGUEJIOFOR, C. U., MEIER, J., GORT, G., COMANS, R., MÄDER, P., BRUSSAARD, L. & DE GOEDE, R. 2019. Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. *Ecological Indicators,* 99**,** 38-50.

BOULESTREAU, Y., CASAGRANDE, M. & NAVARRETE, M. 2023. A method to design coupled innovations for the agroecological transition. Implementation for soil health management in Provencal sheltered vegetable systems. *Agricultural Systems,* 212.

BROCK, C., OLTMANNS, M., MATTHES, C., SCHMEHE, B., SCHAAF, H., BURGHARDT, D., HORST, H. & SPIEß, H. 2021. Compost as an Option for Sustainable Crop Production at Low Stocking Rates in Organic Farming. *Agronomy*, 11.

BURGOS HERNÁNDEZ, T. D., SLATER, B. K., TIRADO CORBALÁ, R. & SHAFFER, J. M. 2019. Assessment of long-term tillage practices on physical properties of two Ohio soils. *Soil and Tillage Research*, 186**,** 270-279.

CÁRCELES RODRÍGUEZ, B., DURÁN-ZUAZO, V. H., SORIANO RODRÍGUEZ, M., GARCÍA-TEJERO, I. F., GÁLVEZ RUIZ, B. & CUADROS TAVIRA, S. 2022. Conservation Agriculture as a Sustainable System for Soil Health: A Review. *Soil Systems*, 6.

DAVERKOSEN, L., HOLZKNECHT, A., FRIEDEL, J. K., KELLER, T., STROBEL, B. W., WENDEBERG, A. & JORDAN, S. 2022. The potential of regenerative agriculture to improve soil health on Gotland, Sweden. *Journal of Plant Nutrition and Soil Science*, 185**,** 901-914.

DAVIS, A. G., HUGGINS, D. R. & REGANOLD, J. P. 2023. Linking soil health and ecological resilience to achieve agricultural sustainability. *Frontiers in Ecology and the Environment*.

DEGUINE, J. P., AUBERTOT, J. N., BELLON, S., CÔTE, F., LAURI, P. E., LESCOURRET, F., RATNADASS, A., SCOPEL, E., ANDRIEU, N., BÀRBERI, P., BECKER, N., BOUYER, J., BRÉVAULT, T., CERDAN, C., CORTESERO, A. M., DANGLES, O., DELATTE, H., DINH, P. T. Y., DREYER, H., DURU, M., FLOR, R. J., GARDARIN, A., HUSSON, O., JACQUOT, M., JAVELLE, A., JUSTES, E., LAM, M. T. X., LAUNAY, M., LE, V. V., LONGIS, S., MARTIN, J., MUNIER-JOLAIN, N., NGUYEN, N. T. T., NGUYEN, T. T. N., PENVERN, S., PETIT, S., POISOT, A. S., ROBIN, M. H., ROLLAND, B., RUSCH, A., SABOURIN, E., SANGUIN, H., SARTHOU, J. P., SESTER, M., SIMON, S., SOURISSEAU, J. M., STEINBERG, C., TCHAMITCHIAN, M., THOUMAZEAU, A., TIBI, A., TIVET, F., TIXIER, P., TRINH, X. T., VIALATTE, A., WYCKHUYS, K. & LAMICHHANE, J. R. 2023. Agroecological crop protection for sustainable agriculture. *Advances in Agronomy.* Academic Press Inc.

DORAN, J. W. & ZEISS, M. R. 2000. Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology*, 15**,** 3-11.

DROTTBERGER, A., MELIN, M. & LUNDGREN, L. 2021. Alternative food networks in food system transition—values, motivation, and capacity building among young swedish market gardeners. *Sustainability (Switzerland)*, 13.

EU 2023. Opinion of the European Economic and Social Committee: 'Towards a European Food Policy Council as a new governance model in the future EU framework on Sustainable Food Systems' (own-initiative opinion).

FAO 2008. An Introduction to the Basic Concepts of Food Security. *In:* NATIONS, F. A. A. O. O. T. U. (ed.) *EC - FAO Food Security Programme*. www.foodsec.org.

FORTIER, J. M., SEVERINE VON TSCHARNER FLEMING, T. G. & BILODEAU, M. 2014. *The Market Gardener: A Successful Grower's Handbook for Small-scale Organic Farming*, New Society Publishers.

GLIESSMAN, S. 2013. Agroecology and Going Beyond Organic. *Agroecology and Sustainable Food Systems,* 37**,** 147-148.

GREEN, V. S., STOTT, D. E. & DIACK, M. 2006. Assay for fluorescein diacetate hydrolytic activity: Optimization for soil samples. *Soil Biology and Biochemistry,* 38**,** 693-701.

HEPPERLY, P. R., OMONDI, E. & SEIDEL, R. 2018. Soil regeneration increases crop nutrients, antioxidants and adaptive responses. *MOJ Food Processing & Technology,* 6.

HUBER, S., BERNARDINI, L. G., BENNETT, A., FOHRAFELLNER, J., DOHNKE, K., BIEBER, M., VUOLO, F., MENTLER, A., BODNER, G. & KEIBLINGER, K. 2023. Suitability of microbial and organic matter indicators for on-farm soil health monitoring. *Soil Use and Management*.

KIM, N., ZABALOY, M. C., RIGGINS, C. W., RODRIGUEZ-ZAS, S. & VILLAMIL, M. B. 2020. Microbial Shifts Following Five Years of Cover Cropping and Tillage Practices in Fertile Agroecosystems. *Microorganisms,* 8.

LAL, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science,* 304**,** 1623-1627.

LAL, R. 2015. Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability,* 7**,** 5875-5895.

LAL, R. 2016. Soil health and carbon management. *Food and Energy Security,* 5**,** 212-222.

LANTMET. 2023. *Väderprognos* [Online]. Sveriges lantbruksuniversitet: VPE/SLU Fältforsk Available: https://www.ffe.slu.se/lm/LMHome.cfm?LMSUB=1 [Accessed 01.08.2023].

LEHMANN, A., ZHENG, W. & RILLIG, M. C. 2017. Soil biota contributions to soil aggregation. *Nat Ecol Evol,* 1**,** 1828-1835.

LEHMANN, A., ZHENG, W., RYO, M., SOUTSCHEK, K., ROY, J., RONGSTOCK, R., MAAß, S. & RILLIG, M. C. 2020a. Fungal Traits Important for Soil Aggregation. *Frontiers in Microbiology,* 10.

LEHMANN, J., BOSSIO, D. A., KOGEL-KNABNER, I. & RILLIG, M. C. 2020b. The concept and future prospects of soil health. *Nat Rev Earth Environ,* 1**,** 544-553.

LIANG, X., YUAN, J., YANG, E. & MENG, J. 2017. Responses of soil organic carbon decomposition and microbial community to the addition of plant residues with different C:N ratio. *European Journal of Soil Biology,* 82**,** 50-55.

LIU, H., WANG, X., LIANG, C., AI, Z., WU, Y., XU, H., XUE, S. & LIU, G. 2020. Glomalin-related soil protein affects soil aggregation and recovery of soil nutrient following natural revegetation on the Loess Plateau. *Geoderma,* 357.

LIU, M., HAN, G. & ZHANG, Q. 2019. Effects of Soil Aggregate Stability on Soil Organic Carbon and Nitrogen under Land Use Change in an Erodible Region in Southwest China. *Int J Environ Res Public Health,* 16.

LUCAS, S. & WEIL, R. 2021. Can permanganate oxidizable carbon predict soil function responses to soil organic matter management? *Soil Science Society of America Journal,* 85**,** 1768-1784.

M. TAHAT, M., M. ALANANBEH, K., A. OTHMAN, Y. & I. LESKOVAR, D. 2020. Soil Health and Sustainable Agriculture. *Sustainability,* 12.

MANGALASSERY, S., MOONEY, S. J., SPARKES, D. L., FRASER, W. T. & SJÖGERSTEN, S. 2015. Impacts of zero tillage on soil enzyme activities, microbial characteristics and organic matter functional chemistry in temperate soils. *European Journal of Soil Biology,* 68**,** 9-17.

MCLENNON, E., DARI, B., JHA, G., SIHI, D. & KANKARLA, V. 2021. Regenerative agriculture and integrative permaculture for sustainable and technology driven global food production and security. *Agronomy Journal,* 113**,** 4541-4559.

MOCKSHELL, J. & KAMANDA, J. 2018. Beyond the agroecological and sustainable agricultural intensification debate: Is blended sustainability the way forward? *International Journal of Agricultural Sustainability,* 16**,** 127-149.

MOEBIUS-CLUNE, B. N., MOEBIUS-CLUNE, D. J., GUGINO, B. K., IDOWU, O. J., SCHINDELBECK, R. R., RISTOW, A. J., VAN ES, H. M., THIES, J. E., SHAYLER, H. A., MCBRIDE, M. B., KURTZ, K. S. M., WOLFE, D. W. & ABAWI, G. S. 2017. Comprehensive Assessment of Soil Health – The Cornell Framework, Edition 3.2. *In:* CORNELL UNIVERSITY, G., NY (ed.).

MONTGOMERY, D. R. & BIKLÉ, A. 2021. Soil Health and Nutrient Density: Beyond Organic vs. Conventional Farming. *Frontiers in Sustainable Food Systems,* 5.

MONTGOMERY, D. R., BIKLE, A., ARCHULETA, R., BROWN, P. & JORDAN, J. 2022. Soil health and nutrient density: preliminary comparison of regenerative and conventional farming. *PeerJ,* 10**,** e12848.

MOREL, K. & LÉGER, F. 2016. A conceptual framework for alternative farmers' strategic choices: the case of French organic market gardening microfarms. *Agroecology and Sustainable Food Systems,* 40**,** 466-492.

NGUYEN, T. D., CAVAGNARO, T. R. & WATTS-WILLIAMS, S. J. 2019. The effects of soil phosphorus and zinc availability on plant responses to mycorrhizal fungi: a physiological and molecular assessment. *Sci Rep,* 9**,** 14880.

PAGE, K. L., DANG, Y. P. & DALAL, R. C. 2020. The Ability of Conservation Agriculture to Conserve Soil Organic Carbon and the Subsequent Impact on Soil Physical, Chemical, and Biological Properties and Yield. *Frontiers in Sustainable Food Systems,* 4.

PÉPIN, A., MOREL, K. & VAN DER WERF, H. M. G. 2021. Conventionalised vs. agroecological practices on organic vegetable farms: Investigating the influence of farm structure in a bifurcation perspective. *Agricultural Systems,* 190.

PEREGO, A., ROCCA, A., CATTIVELLI, V., TABAGLIO, V., FIORINI, A., BARBIERI, S., SCHILLACI, C., CHIODINI, M. E., BRENNA, S. & ACUTIS, M. 2019. Agro-environmental aspects of conservation agriculture compared to conventional systems: A 3-year experience on 20 farms in the Po valley (Northern Italy). *Agricultural Systems,* 168**,** 73-87.

POWER, A. G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. *Philos Trans R Soc Lond B Biol Sci,* 365**,** 2959-71.

RAHMAN, M. M., ARAVINDAKSHAN, S., HOQUE, M. A., RAHMAN, M. A., GULANDAZ, M. A., RAHMAN, J. & ISLAM, M. T. 2021. Conservation tillage (CT) for climate-smart sustainable intensification: Assessing the impact of CT on soil organic carbon accumulation, greenhouse gas emission and water footprint of wheat cultivation in Bangladesh. *Environmental and Sustainability Indicators,* 10.

RAY, P., LAKSHMANAN, V., LABBE, J. L. & CRAVEN, K. D. 2020. Microbe to Microbiome: A Paradigm Shift in the Application of Microorganisms for Sustainable Agriculture. *Front Microbiol,* 11**,** 622926.

RILLIG, M. C., AGUILAR-TRIGUEROS, C. A., CAMENZIND, T., CAVAGNARO, T. R., DEGRUNE, F., HOHMANN, P., LAMMEL, D. R., MANSOUR, I., ROY, J., VAN DER HEIJDEN, M. G. A. & YANG, G. 2019. Why farmers should manage the arbuscular mycorrhizal symbiosis. *New Phytol,* 222**,** 1171-1175.

ROSBERG, A. K. & ALSANIUS, B. W. 2022. Crop rotations in organic greenhouse production – effects of increased crop diversity on the soil microbiome. *Acta Horticulturae***,** 47-54.

ROY, D., DATTA, A., JAT, H. S., CHOUDHARY, M., SHARMA, P. C., SINGH, P. K. & JAT, M. L. 2022. Impact of long term conservation agriculture on soil quality under cereal based systems of North West India. *Geoderma,* 405.

SAHU, G., MOHANTY, S. & DAS, S. 2020. Conservation Agriculture- a Way to Improve Soil Health. *Journal of Experimental Biology and Agricultural Sciences,* 8**,** 355-368.

SCHRÖTER, D., CRAMER, W., LEEMANS, R., PRENTICE, I. C., ARAÚJO, M. B., ARNELL, N. W., BONDEAU, A., BUGMANN, H., CARTER, T. R., GRACIA, C. A., DE LA VEGA-LEINERT, A. C., ERHARD, M., EWERT, F., GLENDINING, M., HOUSE, J. I., KANKAANPÄÄ, S., KLEIN, R. J. T., LAVOREL, S., LINDNER, M., METZGER, M. J., MEYER, J., MITCHELL, T. D., REGINSTER, I., ROUNSEVELL, M., SABATÉ, S., SITCH, S., SMITH, B., SMITH, J., SMITH, P., SYKES, M. T., THONICKE, K., THUILLER, W., TUCK, G., ZAEHLE, S. & ZIERL, B. 2005. Ecosystem Service Supply and Vulnerability to Global Change in Europe. *Science,* 310**,** 1333-1337.

SEKARAN, U., SAGAR, K. L., DENARDIN, L. G. D. O., SINGH, J., SINGH, N., ABAGANDURA, G. O., KUMAR, S., FARMAHA, B. S., BLY, A. & MARTINS, A. P. 2020. Responses of soil biochemical properties and microbial community structure to short and long-term no-till systems. *European Journal of Soil Science,* 71**,** 1018-1033.

SEKARAN, U., SAGAR, K. L. & KUMAR, S. 2021. Soil aggregates, aggregate-associated carbon and nitrogen, and water retention as influenced by short and long-term no-till systems. *Soil and Tillage Research,* 208.

SONG, K., ZHENG, X., LV, W., QIN, Q., SUN, L., ZHANG, H. & XUE, Y. 2019. Effects of tillage and straw return on water-stable aggregates, carbon stabilization and crop yield in an estuarine alluvial soil. *Scientific Reports,* 9.

SOONG, J. L., FUCHSLUEGER, L., MARAÑON-JIMENEZ, S., TORN, M. S., JANSSENS, I. A., PENUELAS, J. & RICHTER, A. 2020. Microbial carbon limitation: The need for integrating microorganisms into our understanding of ecosystem carbon cycling. *Global Change Biology,* 26**,** 1953-1961.

STERN, N. 2016. Economics: Current climate models are grossly misleading. *Nature,* 530**,** 407-409.

STRIBLEY, D. P., TINKER, P. B. & SNELLGROVE, R. C. 1980. EFFECT OF VESICULAR-ARBUSCULAR MYCORRHIZAL FUNGI ON THE RELATIONS OF PLANT GROWTH, INTERNAL PHOSPHORUS CONCENTRATION AND SOIL PHOSPHATE ANALYSES. *Journal of Soil Science,* 31**,** 655-672.

TILMAN, D., CASSMAN, K. G., MATSON, P. A., NAYLOR, R. & POLASKY, S. 2002. Agricultural sustainability and intensive production practices. *Nature,* 418**,** 671-677.

TILMAN, D., FARGIONE, J., WOLFF, B., D'ANTONIO, C., DOBSON, A., HOWARTH, R., SCHINDLER, D., SCHLESINGER, W. H., SIMBERLOFF, D. & SWACKHAMER, D. 2001. Forecasting Agriculturally Driven Global Environmental Change. *Science,* 292**,** 281-284.

TITTONELL, P. 2014. Ecological intensification of agriculture—sustainable by nature. *Current Opinion in Environmental Sustainability,* 8**,** 53-61.

TITTONELL, P. 2019. Agroecological transitions: multiple scales, levels and challenges. *Revista de la Facultad de Ciencias Agrarias, Universidad Nacional de Cuyo 2019* Vol.51 No.1 pp.231-246 ref.37

UN. 2015. *Sustainable Development Goals. Transforming our world: the SDGs 2030* [Online]. Available: https://sdgs.un.org/goals [Accessed].

VAN BRUGGEN, A. H. C., SEMENOV, A. M., VAN DIEPENINGEN, A. D., DE VOS, O. J. & BLOK, W. J. 2006. Relation between Soil Health, Wave-like Fluctuations in Microbial Populations, and Soil-borne Plant Disease Management. *European Journal of Plant Pathology,* 115**,** 105-122.

YANG, L., WANG, N., CHEN, Y., YANG, W., TIAN, D., ZHANG, C., ZHAO, X., WANG, J. & NIU, S. 2020. Carbon management practices regulate soil bacterial communities in response to nitrogen addition in a pine forest. *Plant and Soil,* 452**,** 137-151.

ZHU, R., ZHENG, Z., LI, T., HE, S., ZHANG, X., WANG, Y. & LIU, T. 2019. Effect of tea plantation age on the distribution of glomalin-related soil protein in soil water-stable aggregates in southwestern China. *Environ Sci Pollut Res Int,* 26**,** 1973-1982.

ZYSERMAN, F., MONACHESI, L. & JOUNIAUX, L. 2017. Dependence of shear wave seismoelectrics on soil textures: A numerical study in the vadose zone. *Geophysical Journal International,* 208**,** 918-935.

Popular science summary

In times of serious global challenges such as exponentially growing global populations, the vast decline of soil fertility and a severe climate change, the sustainability of our food production systems determines future food security. This research explores the potential of an innovative solution: biointensive market gardening. This method represents a paradigm shift in agricultural practices, emphasizing not just yield maximisation but the holistic health of soil, humans, and the surrounding ecosystems.

At its core, biointensive market gardening employs agroecological principles, emphasising on efficient resource utilization, promoting biodiversity, and providing food security to local communities. Unlike conventional farming practices that often deplete the soil, this method actively improves soil health. This research showcased that by applying key principles involving (1) reducing soil disturbance through gentle farming techniques; (2) enhancing biodiversity through practices like cover cropping and crop rotations; and (3) supporting continuous soil cover, leading to (4) abundant living roots in the soil exhibited notable improvements in soil health parameters. Such enhancements are practically relevant since they translate to essential benefits like (1) carbon sequestration important for climate change mitigation, (2) improved water retention, nutrient availability, and thus soil fertility decreasing the common input dependency of food production systems. Accordingly, increased soil health has a direct correlation with the promotion and acquisition of future food security. Furthermore, this method holds promises beyond soil health: it offers potential avenues to (3) optimize crop nutrition underscoring the ability of biointensive market gardening to enhance both the quality and quantity of vegetable crops, directly corresponding with human well-being and chronic disease prevention. Finally, holistic and health centred market gardening (4) increases the resilience of the production system to environmental stresses, which is especially relevant in times of uncertain climatic conditions due to climate change.

In conclusion, biointensive market gardening emerges as a promising production method in the field of sustainable agriculture. By supporting a symbiotic relationship between food production and environmental stewardship, it offers an attractive solution for a resilient and sustainable future amidst the challenges of the 21st century.

Acknowledgements

Upfront I would like to thank my family, my friends, and my partner for supporting me through this journey. It has been a long one, I am aware, and it has taken a lot of love and care work from us all. Thank you for your patients, your trust, for staying with me, even though I have been abroad for this long. Thank you for sharing a vision with me and empowering me to reach for my stars. I love you all a lot.

Thank you wonderful Alnarp´s Agroecology Farm and the gorgeous farm board that has made this possible - collectively. All the joy and fun we had! For me this farm is not only about producing vegetables but living a future worth living together with my friends. I am so proud of us!

Thank you, Anna Karin, for all your support, your patients, and your knowledge. You have been my guide through the world of Academia and enabled me to research a topic that is meaningful for me. I hope our work continues.

Thank you, Pablo, for being a great role model, for your thoughts and ideas and the work you do. You have been a source of inspiration and faith for this work.

Thank you Partnership Alnarp, SLU Alnarp and the department Biosystems and Technology for the funding of this research and the facilities to make it possible. This has been the academic experience I have dreamed of – thank you for providing this respectful atmosphere and the space for students to develop their own opinion.

Thank you, Zach, for your kind help and support, even though we never met.

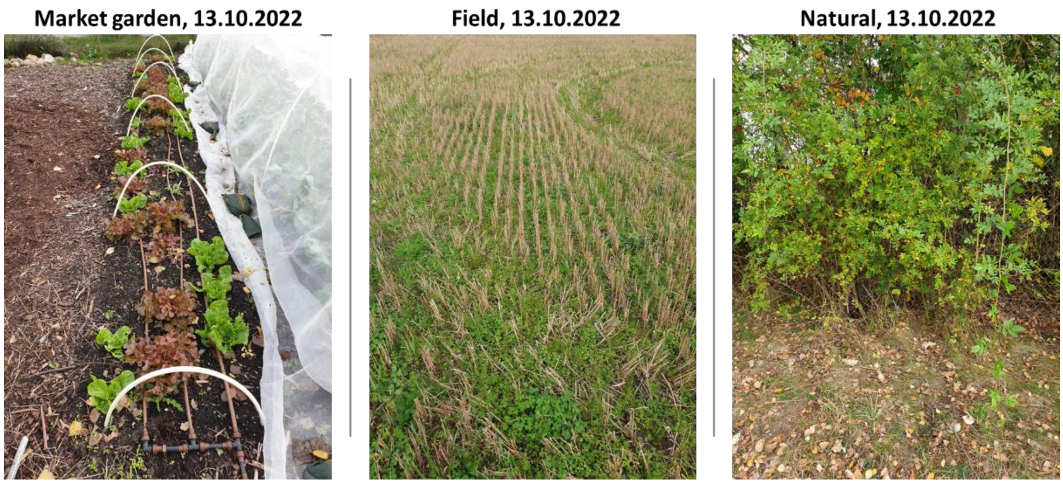
Finally, I would like to give thanks to our beautiful environment. Thank you for allowing us to join your cycle of life, for accepting and returning our care work. Thank you for providing us with life and energy, so abundant and generously.

Erde die uns dies gebracht,
Sonne die hats reif gemacht.
Liebe Sonne, liebe Erde,
eurer nicht vergessen werde.

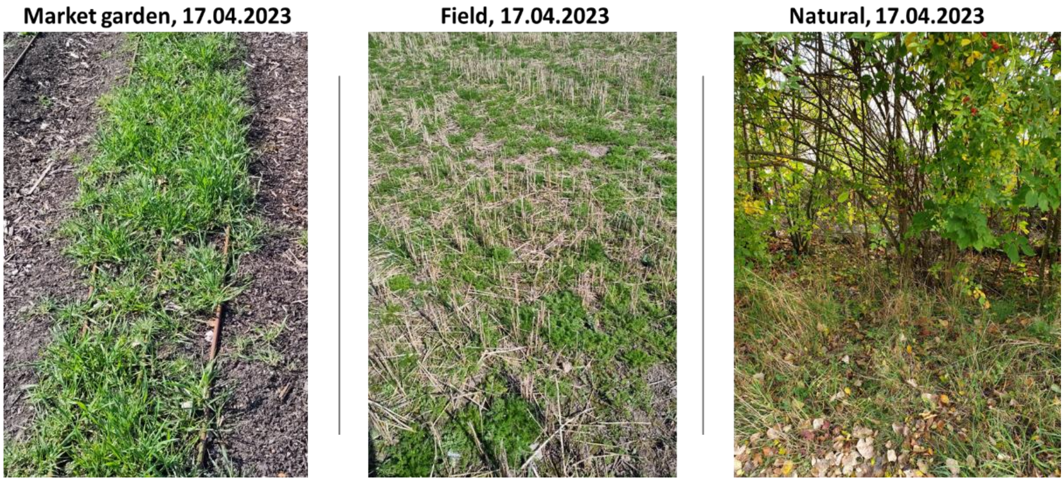
Earth that brought us this,
Sun that made it ripe in bliss.
Dear Sun, dear Earth,
We will not forget your worth.

Appendix 1

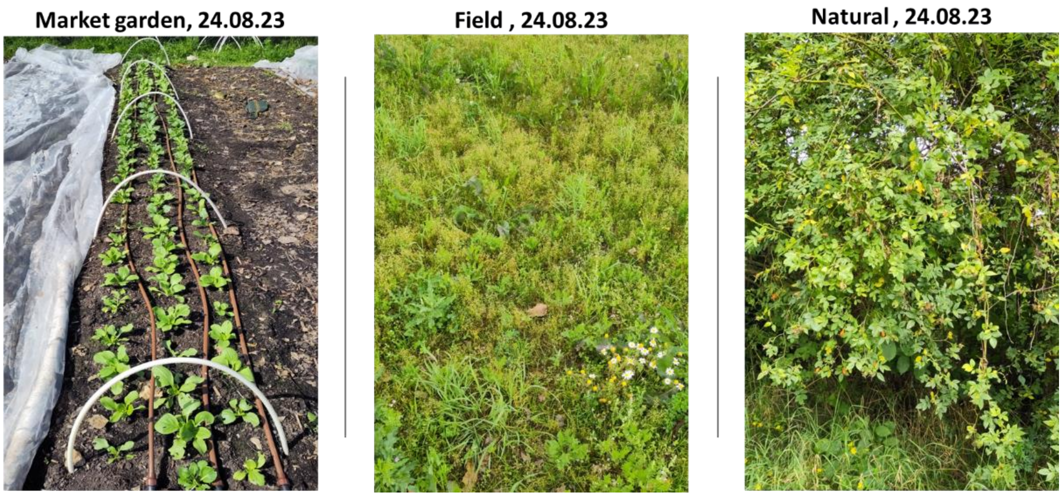
Picture 2: Pictures taken of the research systems market garden (left), field (centre) and natural (right) at the initial sampling date in 2022. The present crops are lettuce in MG, winter wheat in sown with grass-legume ley in F and wild rose in N.



Picture 3: Documentation of the crop status in the research systems MG (left), F (centre) and N (right) at the second sampling date in 2022. Lettuces are present in the market gardening system; winter wheat stalks are left in the field and the wild rose bush is the subject of research in the natural fence line.



Picture 4: Vegetation status of the research systems market garden (left), field (centre) and natural fence line (right) at the first sampling date 2023. The MG sampling was under winter oats, the field had previous year's winter wheat stalks present when sampling. The natural system samples were taken under the wild rose bushes.



Picture 5: Pictures taken of the crops sampled in the research systems MG (left), F (centre) and N (right). The market garden had pack choi and lettuces present at the final sampling, the field system was a grass-legume ley with a lot of unintended weeds and the natural fence line was rose bushes.

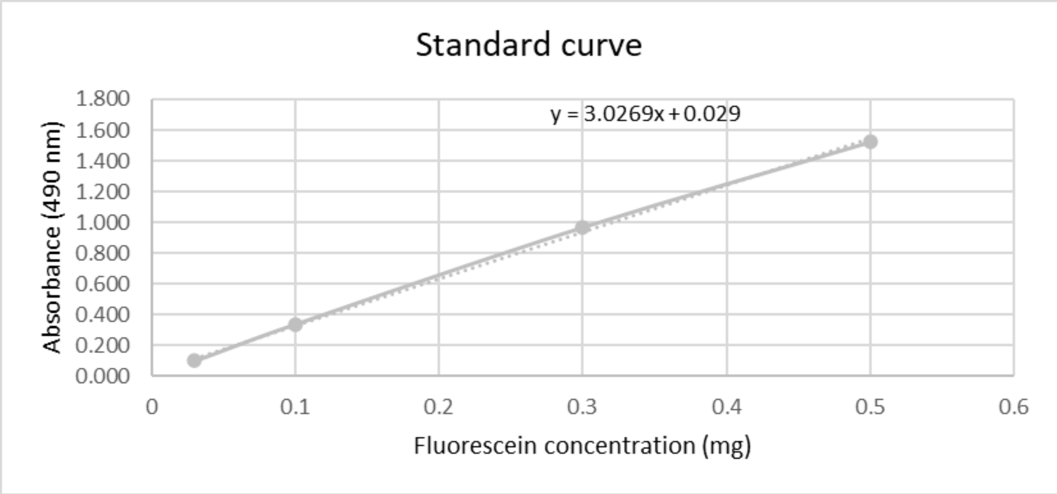


Figure 18: Standard curve obtained from measuring FDA standards of the concentration 0,03, 0.1, 0.3 and 0.5 mg/g. The resulting equation is used for transforming the absorbance values into fluorescein values in mg/g soil.

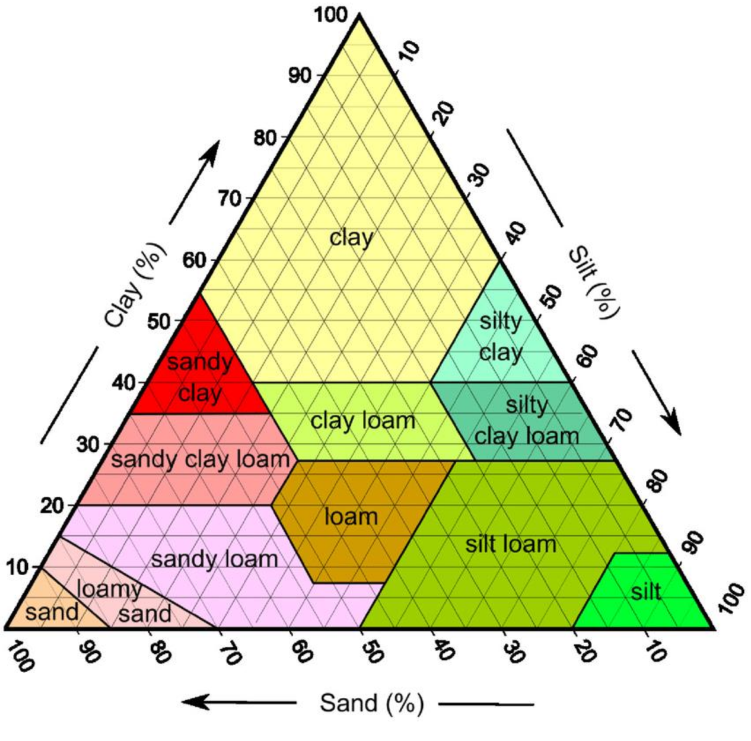


Figure 19: Soil texture triangle, based on U.S. Soil Conservation Service (1987), taken from (Zyserman et al., 2017).

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EUSELI2-00930996
Kundnummer: SL8032729

Uppdragsmärkn.
440 JN

Analysrapport

Provnummer:	**177-2021-09300751**	Provtagningsdatum	2021-09-29
Provbeskrivning:		Provtagare	Jerry
Matris:	Kompost		
Provet ankom:	2021-09-30		
Utskriftsdatum:	2021-11-08		
Analyserna påbörjades:	2021-09-30		
Provmärkning:	2018 0-20 2021-09-29		
Provtagningsplats:	Spillepeng		

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Provberedning krossning, malning	**1.0**			SS-EN 15002:2015-07	b)*
Fukthalt	**44.3**	%	10%	SIS-CEN/TS 15414-2:2014 / SS-EN15414-3:2011	b)*
Glödförlust	**29.9**	% Ts	10%	SS-EN 12879:2000	c)
Glödrest	**70.1**	% Ts	10%	SS-EN 12879:2000	c)*
pH	**8.8**		0.2	SS-EN 15933:2012	c)
Kväve Kjeldahl	**7100**	mg/kg	10%	EN 13342	a)
Kväve Kjeldahl	**1.3**	% Ts	10%	Beräknad från analyserad halt	c)
Ammoniumkväve (NH4-N)	**880**	mg/kg	20%	STANDARD METHODS 1998, 4500 mod	a)
Ammoniumkväve	**0.15**	% Ts	10%	Beräknad från analyserad halt	c)
Ogräs och grobara växtdelar	**0.0**	antal/l		BGK IV B1, 2006	c)*
Stabilitet (självuppvärmning)	**5 färdig**			BGK IV, A1, 2006 / Solvita	c)*
Max temperatur	**21.9**	°C		BGK IV, A1, 2006 / Solvita	c)*
Stabilitet (Solvita)	**6 aktiv**			BGK IV, A1, 2006 / Solvita	c)*
CO2 index	**6**			BGK IV, A1, 2006 / Solvita	c)*
NH3 index	**5**			BGK IV, A1, 2006 / Solvita	c)*
Partiklar <2 mm	**76**	% Ts		BGK II C1 + C2, 2006	c)*
Partiklar >2 och <5 mm	**11**	% Ts		BGK II C1 + C2, 2006	c)*
Partiklar <5 mm	**88**	% Ts		BGK II C1 + C2, 2006	c)*
Sten >5 mm	**4.0**	% Ts		BGK II C1 + C2, 2006	c)*
Synliga föroreningar >2 <5 mm	**0.0**	% Ts		BGK II C1 + C2, 2006	c)*
Synliga föroreningar >5 mm	**0.0**	% Ts		BGK II C1 + C2, 2006	c)*
Kväve N	**1.07**	% Ts	10%	SS-EN ISO 21663:2020	b)*
Kväve N Lev.tillstånd	**0.60**	%	10%	SS-EN ISO 21663:2020	b)*
Arsenik As	**3.6**	mg/kg Ts	25%	SS 028150:1993/SS-EN	c)

Förklaringar

Laboratoriet/laboratorierna är ackrediterade av respektive lands ackrediteringsorgan. Ej ackrediterade analyser är markerade med * AR-003v58

Mätosäkerheten, om inget annat anges, redovisas som utvidgad mätosäkerhet med täckningsfaktor 2. Undantag relaterat till analyser utförda utanför Sverige kan förekomma. Ytterligare upplysningar samt mätosäkerhet och detektionsnivåer för mikrobiologiska analyser lämnas på begäran.

Denna rapport får endast återges i sin helhet, om inte utförande laboratorium i förväg skriftligen godkänt annat. Resultaten relaterar endast till det insända provet.

Sida 1 av 3

Figure 20:Eurofins analysis of the imported Sysav compost, part 1/3. The compost was added to the market gardening system in the beginning of 2022 at a quantity of 15cm / m2, which calculates to about 60kg / m2 of added compost. In the beginning of the second season in 2023, another 10cm layer of compost was added to the market gardening system. Thus, about 100kg / m2 of compost were added to the market gardening system during the research period.

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				ISO 17294-2:2016	
Bly Pb	**19**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 17294-2:2016	c)
Fosfor P	**2300**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Järn Fe	**8400**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Kadmium Cd	**0.41**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 17294-2:2016	c)
Kalcium Ca	**21000**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Kalium K	**7800**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Koppar Cu	**59**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Krom Cr	**31**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Kvicksilver Hg	**< 0.050**	mg/kg Ts	25%	SS 028150:1993/ SS-EN ISO 17852:2008mod	c)
Magnesium Mg	**3100**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Mangan Mn	**250**	mg/kg Ts	30%	SS 028150:1993/SS-EN ISO 17294-2:2016	c)
Natrium Na	**570**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Nickel Ni	**12**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
Svavel S	**1800**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)*
Zink Zn	**170**	mg/kg Ts	25%	SS 028150:1993/SS-EN ISO 11885:2009.	c)
klorid (vattenlöslig)	**1100**	mg/kg Ts		SS-EN ISO 10304-1:2009	d)*
Kol C	**17.9**	% Ts	10%	SS-EN 15936:2012 metodappl. A / SS-EN 13137:2001 metodappl. A	b)*
Manuell fakturering	**Se bifogad rapport**				c)*
C/N-kvot	**14**			Beräkning	b)*
Total kväve N i prov	**7.4**	kg/ton		Beräknad från analyserad halt	c)*
Total Kväve N	**4.5**	kg/m³		Beräknad från analyserad halt	c)*
Ammoniumkväve i prov	**0.88**	kg/ton		Beräknad från analyserad halt	c)*
Ammoniumkväve	**0.54**	kg/m³		Beräknad från analyserad halt	c)*
Total Fosfor P i prov	**1.3**	kg/ton		Beräknad från analyserad halt	c)*
Total Fosfor P	**0.80**	kg/m³		Beräknad från analyserad halt	c)*
Total Kalium K i prov	**4.4**	kg/ton		Beräknad från analyserad halt	c)*
Total Kalium K	**2.7**	kg/m³		Beräknad från analyserad halt	c)*
Total Kalcium Ca i prov	**12**	kg/ton		Beräknad från analyserad halt	c)*
Total Kalcium Ca	**7.3**	kg/m³		Beräknad från analyserad halt	c)*

Förklaringar

Laboratoriet/laboratorierna är ackrediterade av respektive lands ackrediteringsorgan. Ej ackrediterade analyser är markerade med * AR-003v58

Mätosäkerheten, om inget annat anges, redovisas som utvidgad mätosäkerhet med täckningsfaktor 2. Undantag relaterat till analyser utförda utanför Sverige kan förekomma. Ytterligare upplysningar samt mätosäkerhet och detektionsnivåer för mikrobiologiska analyser lämnas på begäran.

Denna rapport får endast återges i sin helhet, om inte utförande laboratorium i förväg skriftligen godkänt annat. Resultaten relaterar endast till det insända provet.

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Figure 21: Eurofins analysis of the imported Sysav compost, part 2/3.

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Total Magnesium Mg i prov	**1.8**	kg/ton	Beräknad från analyserad halt	c)*
Total Magnesium Mg	**1.1**	kg/m³	Beräknad från analyserad halt	c)*
Total Natrium Na i prov	**0.32**	kg/ton	Beräknad från analyserad halt	c)*
Total Natrium Na	**0.20**	kg/m³	Beräknad från analyserad halt	c)*
Total Svavel S i prov	**1.0**	kg/ton	Beräknad från analyserad halt	c)*
Total Svavel S	**0.62**	kg/m³	Beräknad från analyserad halt	c)*

Utförande laboratorium/underleverantör:

a) Eurofins Food & Feed Testing Sweden (Lidköping), SWEDEN, ISO/IEC 17025:2017 SWEDAC 1977
b) Eurofins Biofuel & Energy Testing Sweden AB, SWEDEN, ISO/IEC 17025:2017 SWEDAC 1820
c) Eurofins Environment Testing Sweden AB, SWEDEN, ISO/IEC 17025:2017 SWEDAC 1125
d) Eurofins Water Testing Sweden, SWEDEN, ISO/IEC 17025:2017 SWEDAC 10300

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Frida Svensson, Rapportansvarig

Denna rapport är elektroniskt signerad.

Förklaringar

Laboratoriet/laboratorierna är ackrediterade av respektive lands ackrediteringsorgan. Ej ackrediterade analyser är markerade med * AR-003v58

Mätosäkerheten, om inget annat anges, redovisas som utvidgad mätosäkerhet med täckningsfaktor 2. Undantag relaterat till analyser utförda utanför Sverige kan förekomma. Ytterligare upplysningar samt mätosäkerhet och detektionsnivåer för mikrobiologiska analyser lämnas på begäran.

Denna rapport får endast återges i sin helhet, om inte utförande laboratorium i förväg skriftligen godkänt annat. Resultaten relaterar endast till det insända provet.

Sida 3 av 3

Figure 22: Eurofins analysis of the imported Sysav compost, part 3/3.

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