Sustainability of Permaculture Farming

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This thesis is lovingly dedicated to our children Merle, Bent and Kalle.

May it make a small contribution to protecting your future.

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Abstract

Since its emergence approximately 10 000 years ago, agriculture has formed human lifestyle and facilitated the rise of complex civilizations. At the same time it led to the development of social inequality and allowed the overexploitation of natural resources. These processes in combination with climatic changes and a growing population resulted in the collapse of various advanced civilizations in human history. Today, we face a similar situation with a climate change for which we ourselves are responsible, despite our ability to understand what led to the collapse of past civilizations and to predict future developments.

Modern industrial agriculture largely contributes to threatening environmental issues like climate change, soil degradation and biodiversity loss. Agroecology and permaculture have emerged as sustainable alternatives. While agroecology is a well-established scientific discipline, permaculture focuses on the conscious design of resilient agroecosystems that mimic nature. The second chapter reviews the scientific basis of permaculture's design principles, as proposed by co-founder David Holmgren. We find that permaculture not only builds on scientific evidence but also aligns with agroecological principles and offers additional guidelines for creating resilient farming systems.

However, empirical evidence supporting permaculture’s benefits has been sparse. Therefore, we conducted two studies on commercial permaculture sites in Central Europe to examine the effectiveness of permaculture in both environmental sustainability and crop productivity. The first study examined a wide range of soil and biodiversity indicators on nine permaculture sites. The study found that permaculture sites had 27% higher soil carbon storage, 20% lower soil bulk density, and a 201% increase in earthworm abundance compared to direct control fields of predominant industrial agriculture. Additionally, levels of various soil macro- and micronutrients were higher on permaculture sites, indicating better conditions for crop production. Species richness for vascular plants, earthworms, and birds was also significantly higher on permaculture sites, with increases of 457%, 77%, and 197%, respectively. The second study, focused on the crop productivity of eleven permaculture sites. Using the Land Equivalent Ratio (LER) as an index, the study found that the yields from permaculture sites were comparable to those of industrial agriculture. Specifically, the LER for permaculture was 0.80 ± 0.27 when compared to total German agriculture and 1.44 ± 0.52 when compared to German organic agriculture, both with no significant difference to 1. Together, these studies suggest that permaculture not only offers environmental benefits but also holds promise in terms of crop productivity.

These findings align well with global initiatives such as the "4 per 1000" initiative, the United Nations Decade on Ecosystem Restoration and the United Nations Sustainable Development Goals. Despite promising results, variability in outcomes suggests the need for further research to understand the complex factors influencing permaculture's effectiveness. Further, we advocate for a multi-dimensional approach to large-scale implementation, involving financial restructuring, educational reforms, and the initiation of flagship projects. Given the urgency of environmental crises, we argue that immediate action is imperative, with research serving as a tool for continuous improvement rather than a prerequisite for action.

Chapter 1

General Introduction

Julius Reiff

The Emergence of agriculture

The emergence of agriculture marks a pivotal point in human history, representing a fundamental shift in how societies obtained food and shaped their way of life. The transition from a hunter-gatherer lifestyle to an agrarian one occurred independently in several regions around the world, starting approximately 10,000 years ago (Stephens et al. 2019). There are various hypothetical explanations for this transition. Amongst others, those are based on climatic changes allowing the emergence of dense and easily harvestable stands of wild cereals (Maisels 2003) as well as social changes, such as the emergence of religious symbolism changing the relationship between people and nature (Balter 2007).

In different parts of the world, various plant and animal species were domesticated based on local conditions and resources. To name a few, in the Fertile Crescent, spanning modern-day Egypt, Israel, Lebanon, Syria, Iraq, and Iran, emmer and einkorn wheat, barley, legumes, and goats were among the first species to be domesticated (Brown et al. 2009; Daly et al. 2018). In the Americas, maize, peanut, manioc, and squash were cultivated by indigenous peoples (Balter 2007). Rice and millet cultivation emerged in East Asia, while sorghum was domesticated in Africa (Balter 2007).

The development of agriculture allowed humans to settle in one place, as they no longer needed to follow migrating animals or seasonal plant growth patterns. This led to the establishment of permanent settlements, which eventually grew into towns and cities. Surplus food production enabled the rise of social hierarchies, as some individuals could specialize in non-food-related tasks, such as governance, craftsmanship, or religious roles. This division of labor fostered the development of complex societies, with organized economies, written languages, and centralized political systems. Civilizations like ancient Egypt, Mesopotamia, the Indus Valley, and the Mayans flourished as a result. (Maisels 2003)

The Collapse of civilisations

While agriculture provided numerous benefits, it also had drawbacks. The reliance on a limited number of crops for sustenance, along with growing populations, made societies vulnerable to crop failures and famine. The environmental impact of agriculture, such as deforestation and soil degradation, posed long-term challenges for human societies. Additionally, through the possibility to permanently claim food resources in form of arable land and to store large quantities of durable food supplies, agriculture is suggested one of the primary drivers for the development of social inequality in human history (Price and Feinman 2010).

The reasons for the collapse of civilizations are complex and often unique to each civilization. However, there are some common factors that determined the collapse of most past civilizations. These include climatic changes, social factors such as political instability or social inequality, and environmental damage in form of deforestation and soil degradation (Butzer and Endfield 2012; Good and Reuveny 2009). In many cases, these factors interact and exacerbate each other, leading to a rapid and irreversible collapse of civilizations.

As an example, through widespread deforestation and intense soil cultivation the Mayan civilization faced high levels of soil erosion, leading to declines in food production for an increasing population. This process was amplified by climatic changes and drought events. Social inequality and the inability of the Mayan leaders to adequately respond to this crisis led to class conflicts, peasant revolts and intersite warfare finally causing the civilization to collapse. (Aimers 2007)

Comparable processes led to the collapse of most other advanced civilizations in human history like the Akkadian Empire in Mesopotamia (Butzer and Endfield 2012), the Khmer Empire in Southeast Asia (Diamond 2009) and even the Roman Empire in Europe (Tainter and Crumley 2007). These stories should sound pretty familiar to us nowadays. However, I will explain in the next paragraph, as today we add some technological factors that push this development, even though we are the first civilization being able to know in detail what happened to past civilizations and to predict future developments.

Heading towards the next collapse

Industrial agriculture, characterized by large-scale monoculture, heavy use of chemical fertilizers and pesticides, and factory farming of livestock, has been a significant driver of the Green Revolution, that aimed to increase global food production and alleviate hunger. While the global population more than doubled and the production of cereal crops tripled between 1961 and 2006, the area of land cultivated only increased by 30% (Wik, Pingali, and Brocai 2008). Despite the Green Revolution leading to an overall increase in calorie intake, it resulted in a decrease in dietary diversity for many underprivileged people and did not improve the persistent issue of micronutrient malnutrition (Pingali 2012). Instead, increasing grain production was utilized to facilitate industrialized livestock production disregarding livestock's traditional function to convert non-edible resources like grass or agricultural waste (Horrigan, Lawrence, and Walker 2002). Between 1950 and 2000, meat consumption has doubled among the world's richest 20%, whereas the world's poorest quintile has not increased its consumption of meat much at all (Kent, Heap, and Royal Society (Great Britain) 2000). Furthermore, decreasing food prices and investment-intensive agricultural technologies, developed for favourable areas, led to a further discrimination of small farmers, thus increasing social inequality (Pingali 2012).

Additionally, the environmental footprint of industrial agriculture is significant. In 2015 one third of global greenhouse gas emissions came from the food system (Crippa et al. 2021). In industrialized countries, the total greenhouse gas emissions of the food system's energy, industry and waste management sectors was larger (53%) than those of its land-based sector (Crippa et al. 2021). Recent results suggest, that increases in agricultural productivity since 1961 were already diminished by 21 % due to the impact of anthropogenic climate change (Ortiz-Bobea et al. 2021). An additional 65 million people (10% increase) are estimated to experience food insecurity due to climate change impacts already in 2050 (Nelson et al. 2018). Additionally, large scale deforestation in tropical regions are mainly attributed to agricultural activity and further aggravate climate change (Seymour and Harris 2019).

Furthermore, worldwide soil degradation is already negatively impacting the wellbeing of at least 3.2 billion people (IPBES 2018). Global crop yield losses due to soil erosion equal the removal of 4.5 M ha yr^{-1} from crop production, which equals approximately one soccer field every five seconds (Montanarella et al. 2015). A recent analysis of agricultural soils on all continents shows, that 16% of conventionally managed plots have a lifespan below 100 years until the whole layer of carbon and nutrient rich topsoil, essential for agricultural activity, is lost due to erosion (Evans et al. 2020). For soils kept bare (still occurring periodically on arable land) the share of evaluated topsoils to be completely eroded within the next 100 years increased to 34 %.

In addition to those concerning progressions we already know from past collapses, today's agriculture is also a leading cause of an alarming loss of biodiversity. A study in 2016 estimated that land use and related pressures (e.g. roads) have already caused widespread declines in “local biodiversity intactness”, which is defined as average percentage of natural biodiversity remaining in local ecosystems (Newbold et al. 2016). This reduction goes beyond its proposed planetary boundary across 58.1% of the terrestrial surface, which is home to 71.4% of the global human population. These losses contribute to undermine the stability of global civilization as biodiversity is linked to the critical ecosystem services supplied to food production itself (e.g. pollination, pest control, soil fertility, climate stability) and other human enterprises (Ehrlich and Ehrlich 2013).

In conclusion, while the Green Revolution has boosted global food production, it also created a trade-off between increased calorie intake and decreased dietary diversity, exacerbated social inequality and caused considerable environmental impacts such as greenhouse gas emissions, severe soil degradation and biodiversity loss. These issues, coupled with the threat of anthropogenic climate change, are the reasons why now, for the first time, a global collapse appears likely (Ehrlich and Ehrlich 2013). We must strive for a system that not only increases food production but also ensures dietary diversity, social equity, and environmental sustainability. The future of our planet and the well-being of billions of people depend on humankind’s ability to transform our agricultural systems.

Transformation by design instead of collapse

Addressing the complex challenges that could lead to a global collapse of civilization will likely require a multifaceted approach, with one key area requiring great effort and caution being the prevention of climate-related mass famines (Ehrlich and Ehrlich 2013). Besides the essential task to slow down climate change as much as possible, reducing the chances of a collapse calls for adopting already known environmental-friendly agricultural techniques, even though that may require trading off immediate corporate profits for social benefits or long-term sustainability (Montgomery 2012). Permaculture might be one piece of the puzzle to do so.

Permaculture is an ecological design system that aims to create sustainable and harmonious human habitats by mimicking natural ecosystems (Figure 1+2). It was developed by Bill Mollison and David Holmgren in the 1970s as a response to environmental degradation,

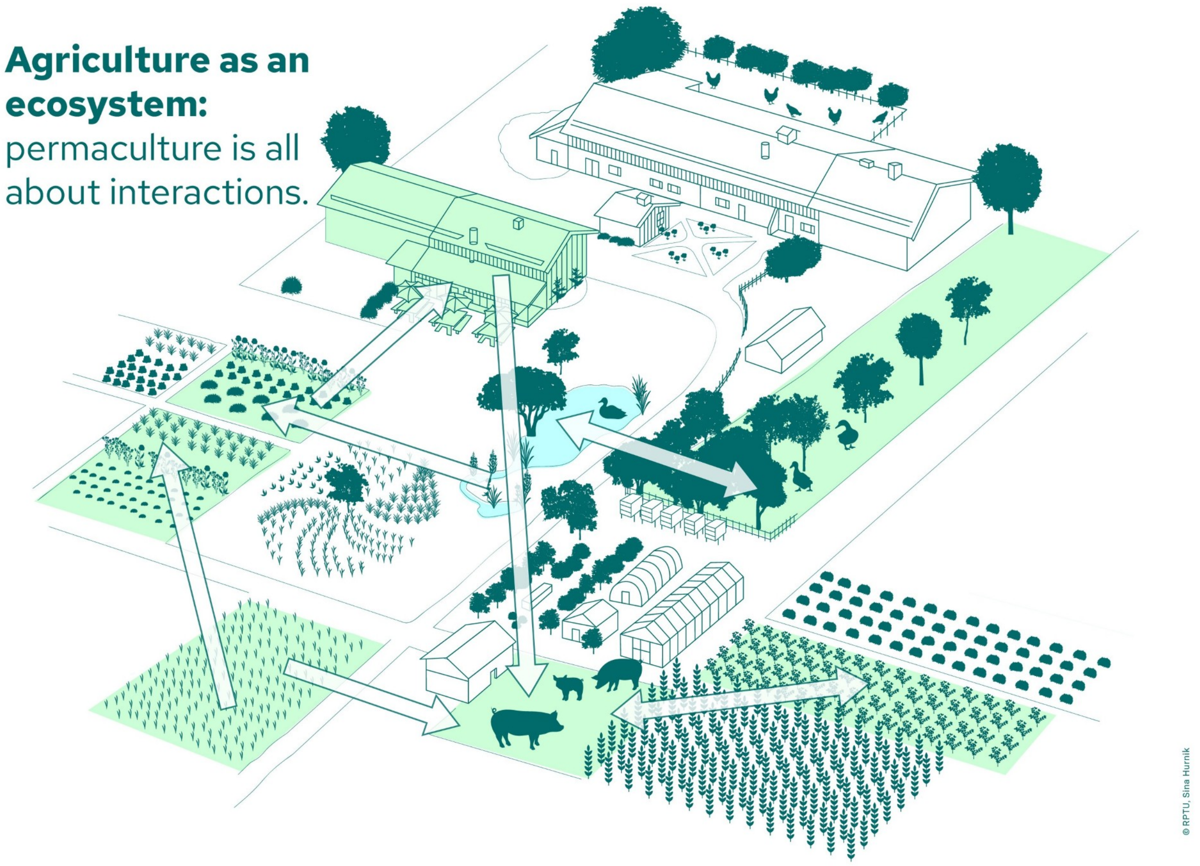

Figure 1: For a stable agricultural system with functioning cycles, the individual components (animal species, crops, trees, farm members) are interwoven into a complex system in permaculture based on nature. Graphic: RPTU, Sina Hurnik

industrial agriculture, and the need for sustainable solutions (Morel, Léger, and Ferguson 2018). Mollison, an Australian ecologist of University of Tasmania at that time, and Holmgren, his student, collaborated to develop the concept of permaculture. They were fascinated by observing the resilience and efficiency of natural ecosystems and sought to apply these principles to human settlements and agriculture.

In addition, Mollison and Holmgren were inspired, by the work of previous pioneers including the following ones. They were influenced by the work of Japanese farmer and philosopher Masanobu Fukuoka, who advocated for natural farming and a deep understanding of natural processes, inspired by the idea of working with nature rather than against it (Fukuoka 2009). Further, Howard T. Odum was a key innovator of systems ecology, focusing on the flow of energy and matter through ecosystems (Odum 1983). He developed models to illustrate these energy flows, which helped to explain how ecosystems function and how they interact with human societies. Odum emphasized the importance of a holistic approach viewing ecosystems as whole systems, rather than just focusing on individual components. Hereby Odum not only influenced the development of permaculture, but also the way we study and understand ecological systems today. Australian engineer Percival Alfred Yeomans, known for his work on Keyline Design (Yeomans 1993), influenced Mollison’s and Holmgren's understanding of water management and landscape design. Yeomans' ideas on contour plowing, water harvesting, and maximizing landscape potential were integrated into the permaculture principles. Additionally, Mollison and Holmgren recognized the sustainable land management practices and ecological wisdom of indigenous cultures worldwide. Observations of how indigenous communities (e.g. the Australian aborigines) lived in harmony with their environments strongly influenced the development of permaculture's regenerative approaches (Mollison 1997).

Mollison and Holmgren recognized the need for a holistic approach that integrates multiple disciplines, including agriculture, architecture, ecology, and sociology, to create a comprehensive framework for sustainable design (Holmgren 2002). The term "permaculture" itself was a blend of "permanent agriculture" which as since been expanded to "permanent culture." It encompasses the idea of designing systems that can be sustained over the long term while meeting the needs of both humans and the environment.

Since its inception, permaculture has evolved and diversified, with practitioners and designers applying its principles worldwide. Permaculture's influence has extended beyond agriculture and gardening, encompassing areas such as sustainable architecture, community development, and ecological restoration (Holmgren 2002). Today, permaculture continues to gain recognition as a viable approach for addressing pressing environmental challenges, such as climate change, soil degradation, and food security (Ferguson and Lovell 2014). Its emphasis on regenerative practices, resilience, and local self-sufficiency aligns with the growing global interest in sustainable living and ecological consciousness.

Overall, permaculture emerged as a response to the need for sustainable alternatives to conventional agriculture and human settlement practices and has evolved into a comprehensive framework for designing regenerative systems that harmonize with nature and promote the well-being of both people and the planet.

Figure 2: Permaculture is a sustainable way of agriculture. The interplay of raised beds, ponds and shrubs in this example not only provides food, but also many ecosystem services and a habitat for animals and plants. Photo: Thomas Baumann, CC-BY-NC (https://creativecommons.org/licenses/by-nc/4.0/deed.en)

The need for evidence

The collaboration between Holmgren and Mollison originated within an academic context and then left it behind. As they developed the permaculture perspective, they distanced themselves from institutional science, focusing instead on enhancing practice and initiating a movement. Their departure from academia was justified — in the 1970s, there was virtually no scientific research to support the practical suggestions they were putting forward. Simply put, science wasn't ready. (Ferguson 2013)

Thus, we now face a lack of scientific evidence on the promising claims made about permaculture (Ferguson and Lovell 2014). However, this evidence is urgently needed for permaculture to gain credibility, avoid being labelled as pseudoscience and to clarify whether it is and important tool for the transformation towards a sustainable (agri-)culture.

Therefore we start in Chapter II with a review of scientific literature. Here we evaluate the design principles proposed by permaculture co-originator David Holmgren (Holmgren 2002) and assess whether they are based on scientific evidence. Further we compare these these principles to those of agroecology, a pretty similar concept which also has been a scientific discipline for a few decades already.

In Chapter III we continue with results of a first extensive study of commercial permaculture plots on a wide range of soil and biodiversity indicators, to evaluate whether permaculture lives up to its claims on environmental sustainability. Therefore we examined nine farms utilizing permaculture in Central Europe and paired control fields of locally predominant agriculture. To strengthen evidence, we provide a comparison of this study's data with larger pre-existing datasets on farmland biodiversity and soil parameters.

Chapter IV is dedicated to the question of whether permaculture can ensure sufficient crop productivity. The transformation of agriculture towards environmental sustainability only makes sense if alternative systems can provide enough food for humankind. For this reason, we collected yield data of eleven permaculture plots in and around Germany. Here, we compare mixed culture systems of permaculture plots with yield data of total and organic German agriculture utilizing the Land Equivalent Ratio (LER).

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Chapter 2

Permaculture—Scientific Evidence of Principles for the Agroecological Design of Farming Systems

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sustainability

MDPI

Review

Permaculture—Scientific Evidence of Principles for the Agroecological Design of Farming Systems

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Abstract: Modern industrial agriculture is largely responsible for environmental problems, such as biodiversity loss, soil degradation, and alteration of biogeochemical cycles or greenhouse gas emission. Agroecology, as a scientific discipline as well as an agricultural practice and movement, emerged as a response to these problems, with the goal to create a more sustainable agriculture. Another response was the emergence of permaculture, a design system based on design principles, as well as a framework for the methods of ecosystem mimicry and complex system optimization. Its emphasis, being on a conscious design of agroecosystems, is the major difference to other alternative agricultural approaches. Agroecology has been a scientific discipline for a few decades already, but only recently have design principles for the reorganization of faming systems been formulated, whereas permaculture practitioners have long been using design principles without them ever being scrutinized. Here, we review the scientific literature to evaluate the scientific basis for the design principles proposed by permaculture co-originator, David Holmgren. Scientific evidence for all twelve principles will be presented. Even though permaculture principles describing the structure of favorable agroecosystems were quite similar to the agroecological approach, permaculture in addition provides principles to guide the design, implementation, and maintenance of resilient agroecological systems.

Keywords: agriculture; agroecology; permaculture; design principles

1. Introduction

In the late 19th century, it became clear that a more efficient agricultural system was needed to feed the people, especially in the Global South [1]. During the 1960s, the green revolution, with the invention of high-yield varieties, synthetic pesticides, and fertilizers, as well as modern machinery, seemed to be the solution to hunger and the prevention of conflicts over nutritional resources [2]. With an increasing yield per unit of land, a decreasing work load, and improved food safety, these technical solutions provided an obvious improvement. However, unfortunately, these advantages came along with an unforeseen price [3–6]. Many of the environmental problems confronting humanity today are related to the modern, industrial agriculture, which is based on the large-scale cultivation of monocultures using heavy machinery, and a large amount of agricultural chemicals, such as synthetic fertilizers and pesticides [7–11]. Also, the ongoing land use change is pushing the earth's ecosystems to the limits of their capacity [6]. Agriculture has a particularly strong impact on (a) biodiversity, (b) soil organic matter, (c) water reservoirs, (d) greenhouse gases, (e) the nitrogen cycle, and (f) the phosphorus cycle:

1.1. Biodiversity Loss

The drastic loss of biodiversity in recent decades is largely due to the intensification and expansion of agriculture [4,8,12–15]. The conversion of natural lands into agricultural uses is especially a serious threat to numerous plant and animal communities (and the ecosystem services they inhabit) [16]. The structural changes connected to the intensification of agriculture lead to a simplification of landscapes, which can thus host fewer species. Most concerning is the considerable loss of diversity in potential habitat colonists. This means that habitats in complex landscapes can be recolonised through a greater diversity of species [17]. The loss of biodiversity poses a risk to human well-being because it is linked to a number of essential ecosystem services, such as natural pest control, pollination, and nutrient cycling [18]. Likewise, all these factors affect agricultural production. These ecosystem services are lost as the agricultural landscape is cleared out [19,20]. However, not only does land use change threaten biodiversity, in addition, the intensive use of pesticides also threatens beneficial insects and thus the food source for predators at higher levels of the food web [15]. This cascade effect also threatens non-target organisms through the use of pesticides [21] and reduces the number of beneficial pollinators [22].

1.2. Loss of Soil Organic Matter

The type and intensity of cultivation has a major impact on the significant loss of soil organic matter through agricultural use [8]. A high proportion of soil organic matter is one of the most important indicators of soil fertility [23] and leads to higher agricultural yields [24,25]. In modern agriculture, much of the soil organic matter is lost, partly through erosion [26,27] and partly through the extraction of organic matter through harvesting crops or soil disturbances due to cultivation [28–30]. High yields can only be maintained through the input of synthetic fertilizers [31].

1.3. Water Usage

In dry climates, high agricultural yields can be considerably attributed to the large-scale irrigation of soils, leading to a virtual water trade between countries when agricultural goods are exchanged [32]. Some new crop varieties even mandate higher water requirements [8,33]. In many regions, this excessive irrigation leads to salinization [34] and to a serious reduction of existing water reservoirs [35]. This development poses considerable risks, especially in the context of climate change [36].

1.4. Greenhouse Gas Emission

Agriculture is currently responsible for about a quarter of net greenhouse gas emissions and thus significantly contributes to climate change [37]. This is due to the use and production of synthetic fertilizers, the use of fossil fuel-intensive machinery, soil degradation, and livestock [33,38]. There are strong indications that climate change in turn has a negative impact on agricultural yields [26], which are predicted to increase in the future [39].

1.5. Nitrogen Cycle

The extraction of nitrogen from the air using the Haber-Bosch process has made the production of large quantities of synthetic fertilizers possible [1]. The effects of this intervention are becoming increasingly visible. Up to half of the amount of nitrogen introduced into the environment is lost in the form of NOx and in turn contributes to climate change [40]. Apart from that, excess nitrogen is also released into watersheds and coastal waters [41] or is lost through surface runoff and soil erosion [42]. In many cases, both processes lead to the eutrophication of adjacent waters [43,44] and the excessive contamination of drinking water with nitrates, posing significant health risks [45,46].

1.6. Phosphorus

Not only is the mining and usage of phosphorous as fertilizer altering the earth's phosphorous cycle, but also the transportation of other agricultural products, like animal feed and crops, contributes to the rising net phosphorous storage in terrestrial and freshwater ecosystems. A study estimates the bioavailable phosphorous stock to be at least 75% greater than preindustrial levels of storage [9]. Similarly to nitrogen, excess phosphorous is transported into terrestrial waterflows and, ultimately, to coastal waters by surface runoff and nutrient leakage [47]. The enrichment of estuaries and coastal waters with phosphorus leads to an increase in toxic cyanobacterial blooms [48]. At the same time, phosphate is a limiting plant nutrient, and, in the form of phosphate rock, a non-renewable resource [49]. Its mining capabilities are supposed to peak in 2030, with mining prices increasing and phosphate quality decreasing already. In addition, toxic by-products, like phosphogypsum, are produced during processing and the phosphates are contaminated with radioactive elements that enter the soil when used as fertilizer. For example, the use of phosphorous fertilizer not only changes the global phosphorous balance, but also contributes to chemical pollution of the soil and the growing of toxic phosphogypsum stockpiles, which pose the risk of leakage into groundwaters [50].

All these factors carry the risk of destroying vital functions of the Earth's ecosystems and threatening our human food supply. Therefore, agricultural systems need to be redesigned. As an alternative for the design of land use systems, agroecology is often discussed in science and many of its methods are studied in detail. In contrast, permaculture, as another approach that promises sustainable solutions for the human supply of goods and resources, is only marginally represented in the scientific literature [51]. The first aim of this review is to analyse to which degree permaculture is based on scientific evidence. On this basis, we secondly aim to identify similarities and differences to agroecological principles.

Within agroecology, the application of principles as a framework for the redesign of agriculture has emerged in recent years. The originators of permaculture have already formulated such principles in the 1980s. They were continuously ameliorated and then applied in the design of land use systems. Although the principles as a whole have not yet been scrutinized, many studies allow the validation of each individual principle against a scientific background. It is shown that despite the lack of representation of permaculture in science, there is some evidence that permaculture has the potential to contribute to the sustainable transformation of agriculture.

2. Agroecology

The term, agroecology, first emerged in modern science when concepts of ecology found their way into agronomy [52,53]. For about three decades, agroecology was almost uniformly used to describe the ecology of agricultural systems with respect to soil science, plant science, insect ecology, and their interactions [54–58]. In the second half of the last century, agroecology developed in parallel with the emergence of organic farming [59]. Some people used the term to promote a paradigm shift from industrial agriculture, driven by the Green Revolution, towards sustainable agriculture based on ecological principles [60–62]. At the same time, other authors kept the original interpretation [63]. Today, agroecology is widely recognised as a scientific discipline, investigating ecological principles, functions, and processes in agricultural systems to create sustainable agricultural systems [64]. With the application of scientific results to agricultural practices, agroecology has also developed into a generic term for the application of specific agricultural techniques that no longer focus solely on production, but on the preservation of the ecosystem [65]. In this context, agroecology became a practical tool for farmers. Since agroecology is mostly practiced by peasant farmers around the world, it has increasingly emerged as a social movement that is working for a more ecologically and socially balanced food system, especially in the countries of the global South [66]. This includes not just food production, but also processing, distribution, and waste management [67], as well as a policy framework for integrating social processes and participation [68]. These aspects support agroecology as a social movement, but have only received recognition when the problems related to modern agriculture became clear, promoting the need for new agricultural practices [64].

The latest interpretations of agroecology recognise all different aspects and describe agroecology as a science discipline and practical application as well as a movement [69,70]. For a detailed description of the history of agroecology see [69,71].

Given the use in a variety of contexts, the multiple meanings of agroecology should be acknowledged. However, the commonality of all definitions lies in an emphasis on an agricultural system that complies with ecological, social, and economic sustainability. On the ecological level, it is about agricultural low input practices that support nature's production, regeneration, and regulatory functions instead of continually maintaining systems optimized for machine use through large amounts of external energy input. The striving for social justice, participation, and autonomy, especially among peasant farmers and the growing community of female peasant farmers, is widely associated with agroecology. In addition, there is a strong engagement for economic independence of peasant farmers in the agroecology community. Agricultural corporations especially foster the threat of economic dependence, while agroecological practitioners try to overcome economic growth logic and money as being the guiding maxim for action. It is replaced by social justice and ecological sustainability.

Agroecology Principles

Today agroecology is still a niche phenomenon, at least in industrialised countries. Even if a transition towards sustainable agriculture is urgently needed, path dependencies and missing or slow policy measures hinder its implementation. However, even if these social challenges can be overcome, the conversion of agriculture from a high input monoculture management system to a diversified system with low external inputs [72] requires a comprehensive framework [73]. Gliessmann describes the necessity to use ecosystem processes and functions as guidelines for the redesign of agricultural systems since a mere substitution of external inputs with biological means and increasing efficiency are not sufficient to attain sustainability [71]. Reijntjes et al. have suggested the use of the following set of ecological principles [74]:

1. Enhance recycling of biomass and optimizing nutrient availability and balancing nutrient flow;
2. securing favorable soil conditions for plant growth, particularly by managing organic matter and enhancing soil biotic activity;
3. minimizing losses due to flows of solar radiation, air, and water by way of microclimate management, water harvesting, and soil management through increased soil cover;
4. species and genetic diversification of the agroecosystem in time and space; and
5. enhance beneficial biological interactions and synergisms among agrobiodiversity components, thus resulting in the promotion of key ecological processes and services.

For Altieri and Nicholls, these principles result in certain agroecological techniques, such as polycultures, crop rotation, agroforestry, cover crops, and animal integration [75]. In addition, according to Vandermeer [76] and Pretty [77], sustainability needs to address farming systems beyond the mere form of cultivation by:

- Optimizing the use of locally available resources by combining the different components of the farm system [...];
- reducing the use of off-farm, external, and non-renewable inputs with the greatest potential to damage the environment or harm the health of farmers and consumers [...];
- relying mainly on resources within the agroecosystem by replacing external inputs with nutrient cycling, better conservation, and an expanded use of local resources;
- working to value and conserve biological diversity, both in the wild and in domesticated landscapes, and making optimal use of the biological and genetic potential of plant and animal species;

- improving the match between cropping patterns and the productive potential and environmental constraints [...]; and
- taking full advantage of local knowledge and practices, including innovative approaches not yet fully understood by scientists although widely adopted by farmers.

With regard to the conservation of biodiversity in productive landscapes, Fischer et al. proposed pattern- and process-oriented strategies for the design and management of agricultural landscapes [78]. For integrated crop-livestock systems, Bonaudo et al. proposed design principles to improve the resilience, self-sufficiency, productivity, and efficiency of the production system [79].

It is important to bear in mind that all these sets of principles are not meant to provide a technical solution that is bound to work in any given place at any time, but are ideas on how to promote key functions of sustainable agroecosystems when applied to a particular region. The practical methods derived from the application of these principles differ and will be specific for the given situation. In addition to guidelines for the design of cropping systems, Malézieux presents a three-step framework for action to guide the incorporation of new farming practices [80]:

Step 1: Observation of the naturally occurring ecosystem;
Step 2: Development and testing of new techniques in experiments; and
Step 3: Implementation of the new techniques by farmers.

3. Permaculture

The concept of permaculture arose from the combination of the words "permanent" and "agriculture", and describes a design system as well as a best practices framework for the creation and management of sustainable and resilient agroecosystems. The co-founder, David Holmgren, defines permaculture as 'consciously designed landscapes, which mimic the patterns and relationships found in nature, while yielding an abundance of food, fibre, and energy for provision of local needs' [81]. Despite permaculture starting as a method of sustainable agriculture, it has evolved to become a holistic design process for complex (eco-)systems and is today also utilized to design social systems.

Permaculture claims to be a concept for the design of sustainable socio-ecological land use systems, recognizing that land use systems are never separated from social systems. For this reason, three basic ethical norms have been formulated, which have to be considered in the design and management of permaculture systems: (1) Care for the earth; (2) care for the people; and (3) set limits to consumption and reproduction, and redistribute surplus (see [81] for further reading).

The most important aspects of permaculture for the planning of agroecosystems are (i) site characteristics; (ii) the interaction between individual elements on several levels, from mixed cultures at the field level to the diversity of land use at the level of the agro-ecosystem; and (iii) the spatial arrangement of the elements as decisive drivers for multiple functions [51,81–83]. This strengthens the natural processes and functions of the landscape [82]. The diversity of land use is described in permaculture as a close integration of terrestrial and aquatic systems, animal husbandry, and field crops in the form of annual and perennial plants [82,84]. Almost none of the methods used in permaculture have been invented by this movement itself. Rather, permaculture can be regarded as a conceptual framework for the evaluation and adoption of existing methods. Therefore, two main criteria are used [51]. Firstly, the imitation of natural ecosystems, which serve as a model for systems with an analogous structure and function, but are endowed with species that generate a yield for mankind [85,86]. Secondly, the optimization of the system in a sense that starting points are sought where the performance of the desired products can be achieved with minimal effort, and functions can be improved beyond the extent of natural ecosystems. This results in a focus on mixed crops and perennial plant species in permaculture systems [81,82,87], which is also increasingly discussed in the scientific literature [88–90].

A distinct element is the permaculture design process [82,91]. It covers the entire process of project development from the first observation to implementation. In an analysis phase, site-specific methods are selected. A permaculture design process is a non-linear process, and the applied observation, analysis, and design methods should prevent typical mistakes when dealing with complex systems [92]. According to Ferguson and Lovell, this design system mainly consists of the permaculture principles and spatial strategies [51].

Permaculture has become an international movement of great public interest [51]. However, there is only minimal coverage of permaculture in the scientific literature. Permaculture practitioners argue that scientists and institutions do not appreciate the radical proposals put forth by permaculture, while, on the other hand, the credibility of permaculture practitioners is lost due to the idiosyncratic use of scientific terms, or the spreading of scientifically unproven claims [50,51].

3.1. Permaculture Principles

Permaculture tries to create resilient living systems that are inspired by processes, structures, and patterns observed in nature. Design principles have emerged that are used as a framework for the design of complex agroecosystems. Some permaculture designers have developed their own sets of principles, depending on the focus of their work [93,94]. The most commonly used set of permaculture principles was developed by co-originator, David Holmgren [81]. These twelve principles are presented as the result of an 'in-depth analysis of the natural environment and pre-industrial and sustainable societies, the application of ecosystem theory, and design thinking'. They claim to provide a framework for the design of sustainable land use and a society within ecological boundaries [81].

The principles are short statements that point the way when dealing with complex systems and give a variety of options for action. The first six principles use a bottom-up approach, while the final six principles can be seen from a top-down designer's perspective. Also, because of this, some overlaps between the principles occur. Trying to *produce no waste* and *applying self-regulation* will lead to *integration rather than segregation* of elements, or *observing and interacting* empowers to be able to *creatively respond to change* [81]. In the design process, it is important not to focus on one or few principles, but to use the set as a whole and create a balance within the system.

Although Ferguson and Lovell have recognised the isolation of permaculture from science [50], we hypothesize that there is strong scientific evidence for the individual principles, underlining their applicability in the redesign of agricultural systems towards sustainability. In the following section, we will scrutinise all twelve principles through the review of scientific studies to illustrate the existence of scientific evidence confirming those principles. In the case where the amount of relevant scientific findings is too extensive, we only give some selected examples. Table 1 provides a summary of those twelve principles along with approach (bottom-up, top-down), relation (agroecosystem structure, design process, management) and examples with evidence mentioned in the following sections.

Table 1. Summary of the twelve permaculture principles proposed by permaculture co-originator, David Holmgren [81], with corresponding approach (bottom-up or top-down), relation (design process, management, agroecosystem structure), and examples with scientific evidence presented in this issue.

Principle	Approach	Relation	Examples with Evidence
I. Observe and Interact	bottom-up	Design process, management	Adaptive management
II. Catch and Store Energy	bottom-up	Agroecosystem structure	Organic mulch application Rainwater harvesting measures Woody elements in agriculture
III. Obtain a Yield	bottom-up	Design process, management	Emergy evaluation Ecosystem services concept
IV. Apply Self-Regulation and Accept Feedback	bottom-up	Agroecosystem structure	Enhancement of regulating ecosystem services Natural habitats in agricultural landscapes Wildflower strips
V. Use and Value Renewable Resources and Services	bottom-up	Agroecosystem structure	Legumes and animal manure as nutrient source Mycorrhizal fungi

Table 1. *Cont.*

Principle	Approach	Relation	Examples with Evidence
VI. Produce no Waste	bottom-up	Agroecosystem structure	Animal manure Human excreta Waste products as animal feed
VII. Design from Patterns to Details	top-down	Agroecosystem structure, Design process	Natural ecosystem mimicry Use of grazing animals in cold and dry climates Structurally complex agroforests in tropical climates
VIII. Integrate Rather than Segregate	top-down	Agroecosystem structure	Integration of livestock in corn cropping Cereals and canola used for forage and grain harvest Integration of fish in rice cropping Polyculture (crops)
IX. Use Small and Slow Solutions	top-down	Agroecosystem structure	Inverse productivity-size relationship Agroforestry systems
X. Use and Value Diversity	top-down	Agroecosystem structure	Plant species diversity Pollinator diversity Habitat diversity Diversified farming systems
XI. Use Edges and Value the Marginal	top-down	Agroecosystem structure	High field border density Field margins Edges with forests
XII. Creatively Use and Respond to Change	top-down	Design process, management	Decision-making under uncertainty Increase ecological resilience Directed natural succession

3.1.1. Permaculture Principle I: Observe and Interact

This principle stands for the method of alternating observation and interaction with a certain system to generate knowledge and experience about it [81]. The scientific management approach related to this principle is called adaptive management, which is a systematic approach for improving resource management by learning from management outcomes [95]. Therefore, multiple management options to reach specific management goals are implemented. The monitoring of system responses to management options gives decision guidance to adjust management practice [96]. Adaptive management was, for instance, successfully used to investigate and improve the effectiveness of agro-environmental schemes in protecting the corn bunting, *Emberiza calandra,* in the UK [97].

Simulation results show that an adaptive management approach yields the best trade-off between agricultural production and environmental services in the case of severe drought in vineyards [98]. However, this approach, with its emphasis on feedback-learning to face the unpredictability and uncertainty that is intrinsic to all ecosystems, is not new. In some traditional management systems, the direction of resource management is guided by the use of local ecological knowledge to interpret and respond to feedback from the environment [99]. While there are still barriers, like maintaining long-term monitoring, to establish adaptive management, the great potential to improve our understanding of important ecological processes necessary for effectively managing biological systems is already visible [96]. Investigations of grazing systems also indicate that the lack of adaptive management in scientific experiments explains why those trials were not able to reproduce the positive effects reported by experienced practitioners [100]. However, a useful addition to this principle, only consisting of observing and interacting, would be the documentation and publishing of observed results to guarantee that generated knowledge can be useful to others dealing with similar situations. The results of research carried out on adaptive management indicate that this approach has the potential to improve agricultural management, especially for ecological resilience. However, to prove the importance of this principle of observing and interacting, it is necessary to scientifically monitor and compare farms strictly sticking to this principle with farms that do not, with regard to ecological resilience as well as productivity.

3.1.2. Permaculture Principle II: Catch and Store Energy

Different sources of energy are covered by this principle: E.g., solar energy, water, wind, living biomass, and waste. According to this principle, energy shall be held within the system as long as possible. This is necessary to be able to use it as long and effectively as possible and to maintain their functions, such as buffering extreme events. The most important storages of future value are fertile soil with high humus content, perennial agroecosystems (especially trees), and water storages, such as groundwater and water bodies [81].

One method to catch and store energy in the form of water, nutrients, and organic matter, while protecting the existing storage of fertile soil, is to apply organic mulch. The application of mulch greatly increases soil water storage efficiency, as well as the water use efficiency of crops, therefore, also increasing crop yields [101–103]. The application of mulch also leads to higher organic matter content in the soil and therefore enhances microbial biomass, soil microbial functional diversity, and nitrogen cycling [104]. Higher contents of soil organic matter lead to higher and more stable yields in agriculture [24,25]. One explanation is the higher capacity of organic matter rich soils to buffer drought stress [105]. Soil fertility is directly linked to soil organic matter. Experiments show that without maintaining natural nutrient cycling via litter decomposition, and without supplementary fertilization, agriculture is only economical for 65 years on temperate prairie, for six years in tropical semi-arid thorn forest, and for no more than three years in Amazonian rainforest [106]. At the same time, the application of mulch showed to be highly effective in preventing soil erosion achieved by reducing runoff and increasing infiltration [107–110]. The capture and storage of rainwater in the soil can be enhanced through rainwater harvesting (RWH) measures. These include linear contour structures, like bunds or grass strips, terracing, semi-circular bunds, and pitting [111]. This mainly helps to overcome drought events [112], leading to increased food security [113–115] and income for farmers [113,116–118]. However, RWH measures also enhance ecosystem services, such as groundwater recharge [119,120], nutrient cycling [121,122], and biodiversity [123,124].

The incorporation of woody elements, such as trees, shrubs, and hedges, into agriculture also represents an application of this principle, amongst others, through the storage of carbon. Different options of land stewardship have a high potential for climate change mitigation, out of which reforestation has the greatest overall potential, and the incorporation of trees in croplands has one of the highest potentials for agriculture and grasslands [125]. Apart from a highly needed climate change mitigation potential, those measures also provide benefits, such as habitats for biodiversity, enhanced soil and air quality, and improved water cycling [125].

3.1.3. Permaculture Principle III: Obtain a Yield

The (farming) systems designed and managed with permaculture have to obtain a sufficient yield, and to supply humans with food, energy, and resources. However, this principle also aims at the efficiency of production, as our "yield" is low if we have to put in a lot of effort, energy, and resources to obtain it. Apart from that, this principle also calls for a more holistic understanding of yield, not only an economic one, but also ecologic and social yields [81].

Emergy analysis is a value-free environmental accounting method based on a holistic systems concept, which is suitable to measure the yield of agro-ecosystems in this sense of efficiency. Emergy is defined by Howard Odum as the available energy of one kind that has already been used to make a product or provide a service [126]. It is usually measured in solar emergy joules (sej), and allows the calculation of various indices. The emergy yield ratio (EYR) provides information on how much emergy output is generated by the system per input of the economy, while the renewability (REN) gives the share of emergy of an output that is provided by renewable natural resources or services [127]. Recent research shows that our modern food production systems are highly inefficient in terms of resource and energy consumption. Corn production in the USA had an EYR of only 1.07 with an REN of 5% [128], while the EYR of conventional pig production was even lower at 1.04 and an REN of 26% [129]. Numerous methods used in permaculture are derived from indigenous people, such as the traditional Lacandon Maya agroecosystems in Mexico. These systems cycle through three stages of production, starting with field crops, progressing to shrubs and then to the trees, before returning to field crops. Therefore, they direct natural succession and are able to yield resources from a polyculture with as many as 60 plant species and without inputs of seeds, fertilizer, or pesticides [130,131]. For six of those systems analysed, the EYR ranged from 4.5 to 50.7 with an REN ranging from 0.72 to 0.97, indicating a high level of sustainability [131]. However, land productivity in terms of the calories of these systems is much lower compared to modern corn production [128]. As this principle also calls for obtaining a yield to feed the people, a combination of efficiency and sustainability, as well as land productivity, should be aspired to. However, this combination is probably the most difficult point in agroecological systems, at least when compared to modern, industrial agricultural production. At first sight, this looks like an approval of the 'land-sharing' approach. However, permaculture is a site-specific and context-based design system. Therefore, we would conclude that it depends on the context of the farm and/or region whether a 'land-sharing', a 'land-sparing', or a combination of both approaches is most favourable to reach the goal of ensuring the resilience of the whole system, while producing enough food.

The call for a more holistic understanding of yield associated with this principle is comparable with the concept of ecosystem services. Scientists try to use this concept to value ecological as well as cultural services to advance the appreciation of non-monetary services provided by nature [132]. Hereby, a holistic understanding of yields from ecosystems is also demanded.

This principle is especially crucial as it calls for a sufficient yield of agricultural products while maintaining a high efficiency in terms of resource and energy consumption as well as ecological and social 'yields'. To further investigate this principle, research has to be carried out, including the evaluation of land productivity of permaculture or similar systems. This is crucial to evaluate whether such systems, besides improving ecological functioning, have the potential to feed the growing world population.

3.1.4. Permaculture principle IV: Apply Self-Regulation and Accept Feedback

The goal of permaculture is to create systems as self-sustaining and self-regulating as possible. Positive feedback accelerates growth and energy accumulation within the farming systems. This is best used in the early phase. Negative feedback, the more important one, protects the system from instability or scarcity through miss- or over-usage. Additionally, each element within a land use system should be as self-reliant as possible to increase the resilience against disturbances [81].

The enhancement of regulating ecosystem services, such as natural pest control, pollination, nutrient cycling, and soil and water quality regulation, are the most common applications of this principle. Strengthening of stabilizing feedbacks in ecological systems, such as those regulating ecosystem services, helps to maintain a favoured and resilient regime of the ecosystem and increases robustness against external stress, e.g., climate change [133].

In the case of insect pollination, this ecosystem service is jointly responsible for a stable (low variability) yield of dependent crops [134]. Increasing the proximity to and the sharing of natural habitats might be one way to apply self-regulation, as this increases the temporal and spatial stability (high predictability and low variation during the day and among plants, respectively) of the pollination service [135].

The reintroduction of flower rich habitats into the agro-ecosystem is another measure to apply self-regulation through the enhancement of the stabilizing ecosystem service of natural pest control. Perennial, species-rich wildflower strips were able to enhance natural pest control and thereby to increase yields from adjacent wheat fields by 10% [136]. A reduced need for pesticide use leads to a lower impact on biodiversity and thereby again increases ecosystem stability through biodiversity-related ecosystem services, such as pollination and pest control [18]. At the same time, the dependency of the farm on agrochemicals decreases, making the farm itself more self-reliant.

3.1.5. Permaculture principle V: Use and Value Renewable Resources and Services

The use of renewable resources and services is necessary to stop the exploitation of non-renewable resources, which, in the long run, undermines the functionality of the whole system. Plants might be used as an energy source, building material, and soil improvers, while examples for animals are herding dogs, animals for soil cultivation, and draught animals. This principle also covers the use of wild resources (fish, game, wood), which should be used sustainably to maintain the renewability of these resources. Overall, this principle focuses on maximizing the use and functioning of ecosystem services [81].

One well studied example for this principle is the use of nitrogen fixing plants (legumes) or animal manure instead of mineral nitrogen fertilizer. Firstly, mineral nitrogen fertilizer contributes 40–68% to farm energy demand [137] and thereby greatly increases the net global warming contribution of farming systems [138]. Alternatively, the energy demand of legume nitrogen fixation is provided by solar radiation and animal manure is available as a waste product. At the same time, animal manure and legume-based systems show higher yield resilience to drought stress as well as increased soil carbon stocks [139]. Animal manure is also proposed to be a renewable resource to stop micronutrient depletion of soils, which is already interlinked with malnutrition of the population in some regions of the world [140]. It has to be kept in mind that there are trade-offs concerning these alternatives to mineral fertilizer. Legumes reduce land use efficiency when they are only used to replace fertilizer and are not harvested as a crop. In the long run, animal manure is only renewable if animal production, including feed production, is based only on renewable resources. Further issues on animal manure are addressed in Section 3.1.6.

Other renewable service providers linked to this issue are mycorrhizal fungi. Mycorrhizal fungi are more abundant with organic fertilization [141], while mineral nitrogen fertilization decreases the diversity of mycorrhizal fungi [142]. Mycorhizzas increase the water and nutrient uptake of plants and thereby enhance plant growth and yield, especially under drought conditions [141,143,144].

There are only a few scientific results dealing with working animals as renewable resources. Most of them are investigating draught animals in countries of the global South. Results indicate that primary energy consumption is lower when using cattle for ploughing compared to tractors [145]. However, we could not find sufficient scientific evidence for the comparison of animal work with machinery in agriculture. Important issues to be investigated according to this comparison are energy efficiency and resource consumption, labor productivity, and environmental impacts, such as soil erosion and greenhouse gas emissions.

3.1.6. Permaculture Principle VI: Produce No Waste

This principle aims at mimicking the natural pattern of exchange and cycling of matter and energy. In natural living systems, no waste occurs as every output of an element (a species) is used by another element. This is why waste could also be seen as an output, which is not used by the system. According to this, all waste should be seen as a resource that should be used to be as effective as possible [81].

The most important example for this principle from modern agriculture is possibly animal manure. Through the separation of plant and animal production in industrial agriculture, animal manure became a waste and a problem. This is due to huge animal production systems concentrating in some regions, while feeds, depending on fertilizer input, are produced elsewhere. Through land application, the high amount of animal manure produced in some regions leads to environmental problems, like eutrophication of ground and fresh water, heavy metal accumulation in top soils, and the emission of ammonia, greenhouse gases, and noxious odours [146,147]. However, recent studies show that in other regions and in lower concentrated land, the application of animal manure has huge benefits. It is a valuable resource to enhance plant nutrient availability (including micronutrients), water holding capacity, soil structure, organic matter content, and carbon storage [146,148–150]. Even if animal manure is applied on agricultural land at reasonable rates, storage and transportation can still cause environmental problems, such as ammonia and greenhouse gas emissions [147,151]. By designing smaller and integrated agricultural systems (see Sections 3.1.8 and 3.1.9), animal manure can lose its waste character while maintaining a high quality and fertile soil.

Even more important might be the high amount of waste of human excreta. Human excreta is a valuable resource of nutrients needed in agricultural production. The application of human excreta as fertilizer is still common in parts of the world, e.g., in Vietnam [152]. Urine is especially valuable as it contains 50–90% of the nutrients of human excreta. It also has a high hygienic quality as it only contains few enteric microorganisms [153]. To improve the hygienic quality of human faeces, a common practice is composting human excreta, which can strongly decrease pathogenous bacteria and parasites [152,154]. However, land applications of human excreta is still a critical topic as there is still insufficient evidence for the fate of therapeutic agents [155].

Many other examples of using waste products in agriculture have been documented. Feeding a 10% share of dried grape pomace increases the growth performance and health indicators of lambs [156]. Vegetable and fruit waste occurring in high amounts with industrial production could also be used as animal feed [157,158].

3.1.7. Permaculture Principle VII: Design from Patterns to Details

Natural ecosystems should be used as patterns for sustainable land use as natural ecosystems evolved over a long period of time to function under certain environmental conditions [81]. Additionally, landscape patterns, such as geomorphology, catchments, and methods, like zoning, and sectors should be used in permaculture design for effective site planning [81].

In scientific literature, this principle is known as "natural ecosystem mimicry". The main patterns/models that are usable for agricultural ecosystems are grasslands, such as savanna or prairie, dry forests, and tropical rainforests [80]. Large areas on earth are naturally too cold or too dry for agriculture [88]. These are areas where natural grasslands occur as the climate is also not suitable for trees. The natural pattern found here is grasslands crossed by large herds of grazing animals. The strategy here is to use the grazers on natural vegetation and to harvest them for meat (e.g., cattle, sheep, goat) or their metabolites (e.g., milk) [88]. Some authors suggest the application of the natural pattern of densely packed and continuously moving herds through multi-paddock, rotational, cell, or mob grazing to prevent desertification through grazing [100,159]. Areas that are dry, but able to facilitate some trees, normally inhabit savannah like systems. In addition to grazers (or in some cases already crops), trees are included to maintain ecosystem functioning, such as a hydrological balance similar to dry forests [80,85,86]. In temperate regions, forests might be used as models for agroecosystems by combining perennial woody crops, such as nut and fruit trees, with different kinds of animals, such as cattle, sheep, poultry, and pigs [160].There are also areas that are too wet to be suitable for agriculture, namely, the humid tropical lowlands. The trophic complexity of local biota (including pests) and nutrient leaching limit agricultural suitability [88]. The strategy here is to increase usable productivity while maintaining the natural structure by building diverse and structurally complex agroforests containing mostly perennial species, as it has been done successfully by local people for centuries [161,162].

For other planning strategies, such as zoning and sectoring [82,94], no scientific evidence could be found. Further research has to be carried out to investigate whether those planning strategies lead to higher labor productivity through improved farm logistics, as well as higher performance and resilience of agricultural elements through site-specific positioning.

3.1.8. Permaculture Principle VIII: Integrate Rather than Segregate

Biological interactions, especially mutual ones, should be used to increase the productivity and stability of the agroecosystem and to generate synergy effects. Integration of elements enables making use of the multifunctionality of elements, like chickens for pest control when integrated into an orchard system. Integration also allows sustaining important functions of a system through multiple elements, like chickens and fruit trees both covering the function of food production. This leads to higher stability of the agroecosystem through integrated pest control and higher economic resilience as the yield is distributed to two sources [81].

These benefits of re-integrating elements in agriculture, especially crops and livestock, have also been promoted in the scientific literature. This integration of crops and livestock is proposed to help overcome the dichotomy between the increase in agricultural production and the negative environmental impacts. This is achieved through better regulation of biogeochemical cycles, an increase in habitat diversity and trophic networks, and a greater resilience of the system against socio-economic or climate change induced risks and hazards [163]. Case studies from France and Brazil show that increasing the interactions between subsystems decreased dependence on external inputs and increased the efficiency of the farm, leading to a good economic, as well as environmental, performance and an increased resilience against market shocks [79]. Studies from the USA show that integrating livestock in corn cropping systems via cool season pasture significantly increases soil quality indicators, such as organic matter and nutrient content [164]. In Australia, the dual-purpose use of cereals and canola for forage during the vegetative stage while still harvesting for grain afterwards is practiced. This provides risk management benefits, improves soil properties, and is able to increase both the livestock and crop productivity of farms by 25–75% with little increase in inputs [165]. Additionally, findings from Asia show that the integration of fish into rice cropping systems increases crop yields through improved weed and pest regulation, increased nutrient availability, and improved water flows, while additionally yielding fish without additional feed or fertilizer [166–168]. Furthermore, a meta-analysis identified a strong potential of within-field crop diversification (polyculture) for win-win relationships between the yield of a focal crop species and the biocontrol of crop pests [169].

A recent study on 35 self-identified permaculture farms in the United States shows, that most of them rely on mixed annual and perennial cropping, the integration of perennial and animal food crops or even an the integration of production and services such as education [170].

3.1.9. Permaculture Principle IX: Use Small and Slow Solutions

This principle is derived from a fundamental pattern found in living organisms: Cellular design [72]. Functions are covered on the smallest possible level, while larger-scale functions are provided through replication and diversification. This principle includes the assumption that small-scale systems are potentially more intense and productive (such as marked gardening or gardening for self-sufficiency), while slow growing systems are potentially more stable and effective (such as tree-based systems) [81].

Small farms (1–2 ha) cultivate 12% and even smaller family farms (less than 1 ha) cultivate 72% of the word's agricultural land [171], and therefore secure nutrition for the biggest share of the world's population. In the scientific literature, the relationship between farm size and land productivity (output per area) has been widely investigated. An inverse productivity-size relationship, stating that smaller farms are more productive per area, has been observed in Africa [172–175], Asia [176–178], Europe [179], and Latin America [180]. Smaller farms, and therefore field sizes, also lead to a higher amount of field edges, inducing beneficial effects, which will be discussed with principle 11.

Modern arable farming systems undermine ecosystem functioning through the adverse effects of intensive industrial production, such as soil erosion, climate change, and loss of biodiversity [181,182]. Agroforestry systems are slower developing compared to modern arable farming, taking some years to reach full productivity and profitability [183]. However, through the maintenance of ecosystem services, such as erosion control, climate change mitigation, biodiversity, and soil fertility, they maintain ecosystem functioning [90,184]. At the same time, agroforestry systems are proposed to be more resilient to climate change [90,185]. In the long run, agroforestry systems have the potential to be even more productive, when compared to exclusively agricultural systems [183].

The application of animal manure or legumes as fertilizer is another example of a slower solution, compared to the fast availability of nutrients from synthetic or mineral fertilizer. Long term studies show that it takes some years until manure or legume fertilized systems (in this case corn) reach a comparable productivity to systems fertilized with mineral fertilizers [139]. However, in the end, manure and legume fertilized systems were both more resistant to draughts, maintaining their yields in drought years [130]. As mentioned above (see Section 3.1.6) the application of manure also maintains and enhances soil quality and fertility.

As this principle is also aimed at farm setup and development, it is also necessary to investigate from an economical perspective whether small and slow developing farms are more economically stable. Recent results of a case study in France show that it is possible for one person to earn a living from agriculture with relatively low input (e.g., no motorization) on 0.1 ha when using permaculture [186,187].

3.1.10. Permaculture Principle X: Use and Value Diversity

This principle is based on the assumption that diversity is one of the foundations of adaptability and the stability of ecosystems. This is why, also in agroecosystems, the habitat and structural diversity should be maintained, as well as the age, species, variety, and genetic diversity [81].

Many ecosystem services maintaining the functioning of our agroecosystems are related to biodiversity. A meta-analysis shows that increasing biodiversity, in many cases of plant species, has positive effects on productivity in terms of producer and consumer abundance, on erosion control through increased plant root biomass, on nutrient cycling through increased mycorhizza abundance and decomposer activity, and on ecosystem stability through increased consumption and invasion resistance [188]. It has also been shown that increasing pollinator diversity has significant positive effects on the yields of various pollination dependent crops [189,190]. Habitat diversity, in terms of landscape complexity, has positive effects on ecological pest control [191]. As an example, increasing the habitat and flowering plant diversity through artificial wildflower strips can increase yields by 10% in nearby wheat fields through enhanced ecological pest control [136].

The increasing awareness of the importance of this principle – to use and value diversity—can also be seen in the development of diversified farming systems. Diversified farming systems use practices developed via traditional and/or agroecological scientific knowledge to intentionally include functional biodiversity at multiple spatial and/or temporal scales [192]. Several studies show that these attempts in increasing agrobiodiversity and therefore ecosystem services, such as soil quality, carbon sequestration, water-holding capacity in surface soils, pollination, pest control, energy-use efficiency, and resistance and resilience to climate change, are successful [193,194].

The already mentioned study of 36 self-identified permaculture farms in the United States also shows that, apart from diversifying the farming system, this principle is also used to create a high diversity of income. The study indicated significant positive effects of production diversity on labour productivity, probably through production synergies [170,195].

3.1.11. Permaculture Principle XI: Use Edges and Value the Marginal

Edges are potentially more diverse and productive, as resources and functions of both adjacent ecosystems are present. As in agroforestry systems, these edge zones can be increased on purpose to take advantage of this effect. Edge zones can also be planned as an appropriate separation of elements, such as woody strips in between meadows. This principle is also aimed at valuing margins for their often invisible advantages and functions instead of trying to minimize them [81].

Recent scientific results show that increasing farmland configurational heterogeneity (higher field border density) increases the pollination ecosystem service through higher wild bee abundance and an improved seed set of test plants, probably through enhanced connectivity [196]. Investigations at the former Iron Curtain in Germany, where the East switched to large-scale farming while the West maintained small-scale agriculture with >70% longer field edges, show similar results. Here, higher biodiversity was found in the region with small scale agriculture, while the species richness and abundance were also higher in field edges compared to field interiors, indicating a link between biodiversity increase and field edge density [197].

Beyond field edge densities, field margins, often seen as unproductive areas, are also of great importance in maintaining ecosystem services. Margins have a range of associated fauna, some of which may be pest species, while many are beneficial either as crop pollinators or as pest predators, and therefore contribute to the sustainability of production by enhancing beneficial species within crops and reducing pesticide use [198].

Edges with other ecosystems may even have a stronger effect on ecosystems services supporting the agroecosystem. Pollination of coffee in terms of fruit set increased in the transition zone to forest ecosystems due to higher functional pollinator diversity [199], while the quantity and quality of strawberries was higher near pond edges through a higher abundance of pollinators [200]. Increasing edges with other, especially natural, ecosystems leads, in most cases, to a fragmentation of those habitats. Habitat fragmentation is often associated with habitat loss, which has large negative effects on biodiversity [201]. However, an investigation of 118 studies on habitat fragmentation, independent of habitat amount, showed that 76% of significant biodiversity responses to habitat fragmentation were positive [202]. Negative effects of habitat fragmentation per se are likely due to habitat size becoming too small to sustain a local population (e.g., mammalian predators [203]) or to negative edge effects (e.g., increased predation of forest birds at edges [201,204]).

As edges appear to have positive effects, it should be mentioned that edges also have the potential to produce negative effects on agricultural production. In transition zones from forests to agricultural areas, changes in the microclimate and matter cycling occur, some of which are not favorable for crop production, such as shade and resource competition [205,206].

3.1.12. Permaculture Principle XII: Creatively Use and Respond to Change

Natural ecosystems are stable and resilient despite constant change and the influence of disturbances. The potential for evolutionary change is essential for the dynamic stability of ecosystems. That is why such systems should not be considered as being in a fixed state, but as an evolutionary process. The implications for agroecosystem design are to include flexibility to create resilience and to deliberately use natural change, such as succession [81].

Our earth's ecosystems are complex, which means that their responses to human use are generally not linear, predictable, or controllable [207]. Another property of complex systems is the existence of momentum, leading to a temporal dynamic of the system. Coupled with the high replication time of ecological experiments, this limits applied ecological research, leading to a permanent existence of uncertainties associated with ecological systems [208,209]. Therefore, it is essential when dealing with ecological systems to apply decision theory's principles of decision-making under uncertainty [210,211], which will not be worked out in detail here [195]. To be able to creatively use and respond to change, systems need to be monitored and assessed (adaptive management, see Section 3.1.1) [209]. Actions should also be favored that are reversible and robust to uncertainties [212], and that increase the resilience of the (socio-)ecological system [190]. Ecological resilience can be defined as the magnitude of disturbance that an ecosystem can withstand without changing self-organized processes and structures [213]. In general, ecological resilience is based on two pillars: The diversity of habitats, species, and genes [207,209,214] and reservoirs, such as fertile soil, water, or biomass [207].

In the case of natural succession, one example of how to use the dynamics and changes in natural ecosystems through successive planting and the facilitation of usable annuals, herbaceous perennials, shrubs, and trees has already been given. In Mexico, indigenous people use and direct natural succession to create a highly efficient land use system (see Section 3.1.2). Another example on a much smaller temporal scale is rotational or cell grazing (see Section 3.1.7), where only a short, but intense, pulse of disturbance is used to set the grassland system back to an earlier stage of succession, leaving it with enough resources (nutrients) to restart development again [159].

4. Conclusions

Agroecology had been a scientific discipline for a few decades when agroecology principles were defined for the redesign of farming systems. Permaculture is another design approach for sustainable agriculture, which has always been isolated from scientific research. This review has shown that there is scientific evidence for all twelve permaculture principles introduced by David Holmgren. As Ferguson and Lovell have already pointed out, there is a strong overlap with agroecological principles. This holds especially true for principles related to the diversity of habitats, species, genes, the cycling of biomass and nutrients, the build-up of storages of fertile soil and water, and the integration of different elements to create synergies. However, permaculture additionally includes principles to guide the design, implementation, and maintenance of resilient agroecological systems, such as observing and interacting to enable coping with change, using small and slow solutions, and designing from patterns to details. This also shows that permaculture's central focus, in contrast to agroecology, is on the conscious design of agroecosystems, making it a possible link between agroecological research and theory and practical implementation in agriculture. To investigate this hypothesis, and to identify whether permaculture can produce resilient agricultural systems that also ensure a sufficient supply of food and resources for people, scientific research needs to be carried out on existing land use that is designed and managed with permaculture. This is also crucial as the presented permaculture principles were developed as a coordinated and interrelated set. Therefore, the impact of the application of the whole set of principles has to be investigated, rather than the principles investigated separately. Possibly due to the separation from science, and therefore from official education and external funding, known examples for the application of permaculture in agriculture are still rare. However, the results of a recent case study show that it is possible for one person to earn a living from agriculture with relatively low input (e.g., no motorization) on 0.1 ha in France when using permaculture. This example indicates that further research on permaculture systems might be valuable for the sustainable development of agriculture.

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Chapter 3

Permaculture enhances carbon stocks, soil quality and biodiversity in Central Europe.

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Permaculture enhances carbon stocks, soil quality and biodiversity in Central Europe

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Permaculture is proposed as a tool to design and manage agroecological systems in response to the pressing environmental challenges of soil degradation, climate change and biodiversity loss. However, scientific evidence on the effects of permaculture is still scarce. In this comprehensive study on a wide range of soil and biodiversity indicators, we examined nine farms utilizing permaculture and paired control fields with locally predominant agriculture in Central Europe. We found 27% higher soil carbon stocks on permaculture sites than on control fields, while soil bulk density was 20% lower and earthworm abundance was 201% higher. Moreover, concentrations of various soil macro- and micronutrients were higher on permaculture sites indicating better conditions for crop production. Species richness of vascular plants, earthworms and birds was 457%, 77% and 197% higher on permaculture sites, respectively. Our results suggest permaculture as effective tool for the redesign of farming systems towards environmental sustainability.

Our world faces a series of urgent environmental challenges, such as soil degradation, biodiversity loss, and climate change. Agriculture is a major driver for transgressing planetary boundaries of biosphere integrity and biogeochemical flows, as well as for land-system change, freshwater use, and climate change being at high risk[1]. On the other hand, agriculture is severely affected by these global change challenges[2,3]. Hence, rapid and profound changes are required to maintain food security[4] while mitigating climate change and restoring biodiversity on agricultural land[5]. A substantial contribution to climate change mitigation on agricultural land can be accomplished by increasing soil organic carbon by 4‰ or 0.6 t ha^{-1} per year[5]. The process of transferring and storing CO_2 from the atmosphere into the soil as part of the soil organic matter, through plants or other organic solids, is called soil carbon sequestration[6]. It has substantial and technically feasible potential to stabilize the global climate system[7]. In addition, soils richer in carbon and, therefore, of higher quality can stabilize yields under variable climate[8] and mitigate climate-driven declines in agricultural production[8]. Phosphorus is essential for crop production, while its rock resources are finite. Therefore improvements in phosphorus use efficiency are an immediate and urgent need[9]. A higher soil organic matter content improves the availability of phosphorus to crops[10] and enables comparable yields with substantially lower soil phosphorus levels[11]. In addition to nutritional requirements, intact biodiversity is essential for agriculture and food production as greater agro-biodiversity can lead to higher resilience of yields to drought, disease outbreaks, or other stresses[4]. High and stable yields also reduce the need for land clearing and for the use of agrochemicals[12]. Hence, the implementation of agroecological principles has been suggested as a viable way out of the negative feedback loops between agriculture and environmental change[13]. At the same time, agroecology is a methodical approach to meet the requirements of agricultural sustainability in terms of context-specificity, flexibility, and circular management[14], with permaculture providing a framework for the design and management of agroecological systems[15,16].

Permaculture creates agriculturally productive ecosystems that mimic the diversity, stability, and resilience of natural ecosystems[17]. In this context, the term permaculture encompasses a set of agricultural practices, a design system to select, combine, and arrange those practices, and also the resulting agroecological farming system[15]. Permaculture systems are, therefore, highly individual and context-specific, which can be essential for a high degree of sustainability. As a result, it is not possible to establish fixed general guidelines as is the case for organic agriculture. Instead, both agroecology and permaculture are based on sets of principles or elements emphasizing a growing set of favorable agricultural practices[16]. There is a strong overlap in the principles

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of these two approaches, which include the promotion of habitat, species, and genetic diversity, the cycling of biomass and nutrients, the build-up of storages of fertile soil and water, and the integration of different land use elements to create synergies[16]. Hereby, both permaculture and agroecology aim to establish regenerative agriculture in terms of environmental health[18,19]. Furthermore, agroecology has an additional focus on social values, responsibility governance and solidarity economy, while permaculture shows a strong emphasis on the conscious design of such agroecosystems.

The United Nations Food and Agriculture Organization (FAO) proposes agroecology as a key approach to achieving the Sustainable Development Goals (SDG), especially to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture (SDG No. 2)[20]. However, permaculture has received little political or scientific attention while being spread around the world by practitioners and itinerant teachers[15,21]. Permaculture has been claimed to improve soil quality, biodiversity, resource conservation, agricultural sustainability, and food security[22]. Although it can be strongly assumed that soil quality and biodiversity are high in permaculture systems due to permaculture design principles like „Use and Value Diversity"[23], or emphasized practices like organic mulching and no-till cultivation, there is still no scientific evidence on whole permaculture systems worldwide[16].

Many practices in permaculture, such as agroforestry, crop-livestock integration, and promotion of semi-natural habitats, are also applied in agroecology and diversified farming systems, and positive environmental influences were already described in the scientific literature[24,25]. However, agroecosystems are not just a sum of practices, but represent complex systems with many functional interactions[26]. Permaculture takes this into account through a holistic systems design, e.g., the deliberate arrangement of context-specific land use practices and the integration of different practices, as well as management based on systems ecology and precise sustainability ethics[23]. Therefore, it is essential to study whole operating farming systems to explore the full potential of permaculture. While there are numerous studies showing positive effects of isolated agroecological practices on ecosystem services[27,28], there is still a lack of scientific evidence on commercial farming systems with multiple integrated practices, in temperate regions, not only for permaculture but also for agroecology[29,30].

In this study, we investigated eight permaculture sites in Germany and one in Luxembourg from 2019 to 2021, which represent either a whole farm or part of a farm. Permaculture sites had to be designed and managed according to permaculture principles, their production had to be economically self-sufficient and at least two different land use practices (e.g., grazing and fruit trees) had to be integrated. The number and types of land use varied among permaculture sites. At each location, one field of each permaculture land use type was sampled, as well as one direct control field with locally predominant agricultural land use. We investigated soil carbon and various nutrients as chemical soil quality indicators, microbial community structure via phospholipid fatty acids (PLFAs) and earthworm abundance as biological indicators, and soil bulk density as physical indicators. With regard to biodiversity, we investigated the species richness of vascular plants as essential primary producers[31] and the species richness of earthworms as important ecosystem engineers[32]. In addition, we investigated the species richness of birds as a particularly popular and widely monitored group of organisms[33]. As an important habitat indicator for general biodiversity, we determined the proportion of the surveyed area with trees[34]. In addition, interviews were conducted with farmers who manage permaculture sites to gather information on farm characteristics, as well as the usage and intentions behind permaculture practices. Several biodiversity indicators were compared with literature data from a European-wide study of ~150 conventional and organic farms[35]. Some soil quality indicators were compared with arable land and grassland data from the first comprehensive German soil inventory[36].

Results

Permaculture sites showed improved soil organic carbon (Figure 1), soil quality (Figure 2, Figure 3) and biodiversity (Figure 4). Results of statistical models are summarized in Table 3, while post hoc comparisons are displayed in Table 4. Values in the text are given as model-predicted mean ± standard error. Concentrations of soil constituents are given per gram of soil dry matter.

Soil carbon and nutrients

We investigated soil organic carbon content in terms of concentration per gram of soil, as well as soil organic carbon stocks, which refers to the amount of carbon stored in the soil per hectare of land. On permaculture sites soil organic carbon content (3.4 ± 0.3 g 100 g^{-1}) was 71% higher compared to control fields of this study (2.0 ± 0.3 g 100 g^{-1}) as well as 94% higher than on average German arable fields (1.8 ± 0.2 g 100 g^{-1}) and by trend 18% higher than on average German grasslands (2.9 ± 0.2 g 100 g^{-1}; Fig. 1a) according to the first comprehensive soil inventory[36]. Carbon stocks within the first 30 cm were 27% higher on permaculture sites (87 ± 9 t ha^{-1}) compared to control fields (68 ± 8 t ha^{-1}) and 37% higher than on average German arable fields (62 ± 3 t ha^{-1}; Fig. 1c)[36]. There was no significant difference between permaculture sites and average German grasslands (90 ± 4 t ha^{-1}), indicating that permaculture is able to store similar levels of carbon as grassland while still producing a share of arable crops such as vegetables and grains. The proportion of permanent grassland among all permaculture sites was 67% (Table 2). In addition, humic topsoil was 59% deeper on permaculture sites (45 ± 4 cm) compared to control fields (28 ± 2 cm; Fig. 1b), suggesting an even higher difference in organic carbon stock. As only real agricultural land was sampled, the carbon stock values do not take into account other farmland structures such as semi-natural habitats or drive- and pathways.

Six of the nine permaculture sites studied were originally of the same land use as the direct control fields (Table 2). Assuming that carbon stocks were originally similar within pairs of site and control fields and have not changed on the control fields over the years of permaculture establishment, we can roughly estimate a level of carbon sequestration on permaculture sites of 0.82 ± 0.39 t ha^{-1} yr^{-1} in the first 30 cm of topsoil (Fig. 1d).

Analysis of soil nutrients, measured as plant-extractable concentrations except for nitrogen, shows a higher soil fertility on permaculture sites. Total nitrogen concentrations were 63% higher on permaculture sites (354 ± 53 mg 100 g^{-1}) compared to control fields (217 ± 33 mg 100 g^{-1}), 138% higher than on average German arable fields (148 ± 18 mg 100 g^{-1}) and 48% higher than on average German grasslands (240 ± 29 mg 100 g^{-1}; Fig. 2a). Carbon nitrogen ratios on permaculture sites (9.3 ± 0.6) were 10% higher compared to control fields and 13% and 16% lower than on average German arable fields and grasslands, respectively. Phosphorus concentrations were by trend 41% higher on permaculture sites (7.3 ± 3.1 mg 100 g^{-1}) compared to control fields (5.2 ± 2.1 mg 100 g^{-1}; Fig. 2b). Potassium concentrations were 123% higher on permaculture sites (30.6 ± 7.1 mg 100 g^{-1}) compared to control fields (13.8 ± 3.5 mg 100 g^{-1}; Fig. 2c) and Magnesium concentrations were 66% higher on permaculture sites (17.5 ± 2.4 mg 100 g^{-1}) compared to control fields (10.5 ± 1.6 mg 100 g^{-1}; Fig. 2d).

Some soil micronutrient levels were also increased under permaculture. Boron concentration was 51% higher on permaculture sites (0.56 ± 0.13 mg g^{-1} versus 0.37 ± 0.09 mg g^{-1}; Fig. 2e), and zinc concentration on permaculture sites was 80% higher compared to control fields (7.6 ± 1.5 mg g^{-1} versus 4.2 ± 0.9 mg g^{-1}; Fig. 2f). We did not find significant differences in soil copper and manganese levels.

Soil pH was not significantly different between permaculture sites with 6.2 ± 0.2 and control fields with 6.2 ± 0.2.

Soil physics and biology

We investigated the soil bulk density as an indicator of soil compaction and erosion potential. In the deeper topsoil (10–30 cm) soil bulk density on permaculture sites was 20% lower on permaculture sites (1.08 ± 0.05 g cm^{-3}) compared to control fields (1.36 ± 0.05 g cm^{-3}) and 24% and 20% lower than on average German arable fileds (1.43 ± 0.03 g cm^{-3}) and grasslands (1.35 ± 0.03 g cm^{-3}; Fig. 3a),

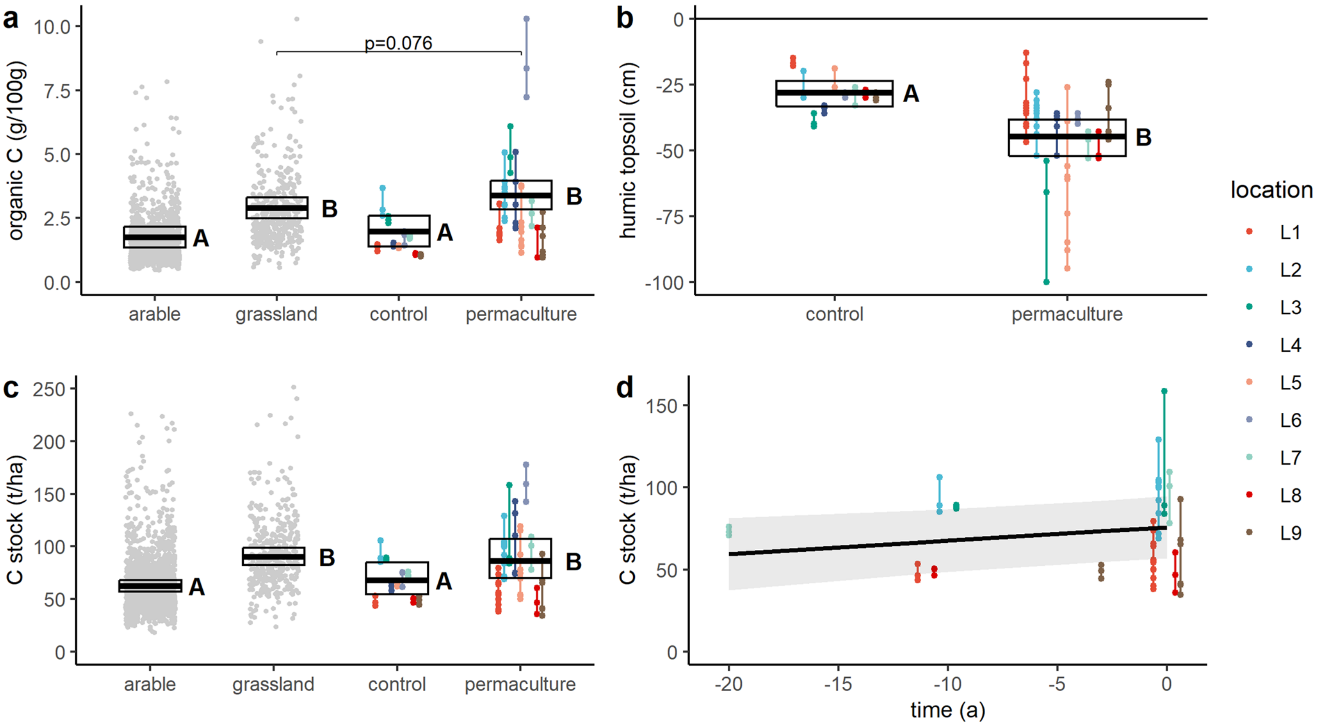

Fig. 1 | Soil organic carbon. a Topsoil (30 cm) organic carbon content on nine permaculture sites, direct control fields of locally predominant agriculture and German grassland ($n = 387$) and arable land ($n = 1683$)[36]. **b** Humic topsoil depth on nine permaculture sites and direct control fields of locally predominant agriculture. **c** Topsoil (30 cm) organic carbon stock on nine permaculture sites, direct control fields of locally predominant agriculture and German grassland ($n = 387$) and arable land ($n = 1683$)[36]. **d** Roughly estimated topsoil (30 cm) carbon sequestration ($p = 0.044$, $\chi^2 = 5.05$, $df = 52$) on six permaculture sites under the assumption that carbon level was originally sufficiently equal on site pairs and did not change on control fields. To set today as a baseline, the age of the permaculture sites was set to zero, and the age of the paired control sites was set to the negative age of the corresponding permaculture site. Here, the black line indicates a significant linear regression slope and 95% confidence interval. Dots indicate individual data points. Colors indicate sampling pair locations and gray dots indicate data points of literature data. Crossbars indicate the model-predicted mean and 95% confidence interval. Treatments not sharing the same letters are significantly different.

respectively[36]. Gravimetric soil water content at sampling was significantly higher on permaculture sites with 31 ± 4% compared to control fields with 21 ± 3%, while there was only a by trend increase in volumetric soil water content (30 ± 4% versus 27 ± 3%).

As macrofaunal indicator of soil quality, we found a 201% higher earthworm abundance on permaculture sites ($153 \pm 57\ \mathrm{m}^{-2}$) compared to control fields ($51 \pm 21\ \mathrm{m}^{-2}$) and a 205% and 331% higher abundance compared to average European organic ($50 \pm 7\ \mathrm{m}^{-2}$) and conventional farms ($36 \pm 5\ \mathrm{m}^{-2}$; Fig. 3b), respectively[35].

To evaluate soil microbiology, we determined PLFA in upper topsoil samples (0–10 cm). As indicator for microbial biomass, we found 42% higher total PLFA concentrations on permaculture sites ($7.6 \pm 1.5\ \mathrm{nmol\ g}^{-1}$) compared to control fields ($4.2 \pm 0.9\ \mathrm{nmol\ g}^{-1}$; Fig. 3c). On permaculture sites, concentrations of bacteria PLFA were 56% higher ($5.5 \pm 1.1\ \mathrm{nmol\ g}^{-1}$ versus $3.5 \pm 0.7\ \mathrm{nmol\ g}^{-1}$) and concentrations of fungi PLFA were 86% higher ($0.9 \pm 0.3\ \mathrm{nmol\ g}^{-1}$ versus $0.5 \pm 0.2\ \mathrm{nmol\ g}^{-1}$). We found a trend to higher ratio of gram-postive to gram-negative bacteria PLFA on permaculture sites with 0.12 ± 0.03 compared to 0.09 ± 0.03. We found no differences in the ratio of fungi to bacteria PLFA and the ratio of arbuscular mycorrhizal to saprophytic fungi PLFA between permaculture sites and control fields.

Biodiversity

We investigated the species richness of vascular plants and earthworms to focus on management effects and minimize the impact of landscape effects that are common in more mobile organisms. Vascular plant species richness was 457% higher on permaculture sites (36 ± 6 species) than on control fields (6 ± 2 species) and 190% and 200% higher than on European organic (19 ± 1) or conventional farms (18 ± 1; Fig. 4a), respectively[35]. Earthworm species richness was by trend 77% higher on permaculture sites (3.3 ± 0.7 species) as on control fields (1.9 ± 0.7 species), while there was no significant difference to other European farms (Fig. 4b)[35]. We also found that bird species richness was 197% higher on permaculture sites (3.6 ± 1.2 species) than on control fields (1.2 ± 0.5 species; Fig. 4c).

As a habitat indicator for biodiversity, the proportion of agricultural area surveyed with trees was higher on permaculture sites with 75 ± 13% compared to European organic farms with 29 ± 4% and conventional farms with 29 ± 3% (Fig. 4d)[35]. This farm-level indicator is not compared to control fields, which in any case contained no trees.

Farm characteristics

The farms utilizing permaculture were, on average, 11 ± 5 years old and had an average area of 13.8 ± 8.4 ha (Table 2). Eight out of nine investigated farms had an area of <20 ha, while only 45% of all farms in Germany fall into this category[37]. Permaculture sites amounted to a mean of 2.8 ± 1.0 ha and were thus clearly smaller than the areas of the farms they belong to. In addition, other sources of income such as non-permaculture agriculture and seminars, many farms provided land for semi-natural habitats to foster ecosystem services and nature conservation. All farms utilizing permaculture were involved in some form of direct marketing, mostly through farm shops, community-supported agriculture, vegetable box delivery, or supply of gastronomy. All permaculture farms work according to the guidelines of organic agriculture, but not always with certification.

The main permaculture practices applied by the study farms can be grouped into three general categories (Table 1). The first category is the integration of land use elements to create synergies and strengthen the resilience and stability of the agroecosystem. Agroforestry has mainly been applied as a combination of fruit trees with grazing livestock or vegetable production. Crop-livestock integration was also practised as intermitted grazing of vegetable or cereal fields by pigs or chickens.

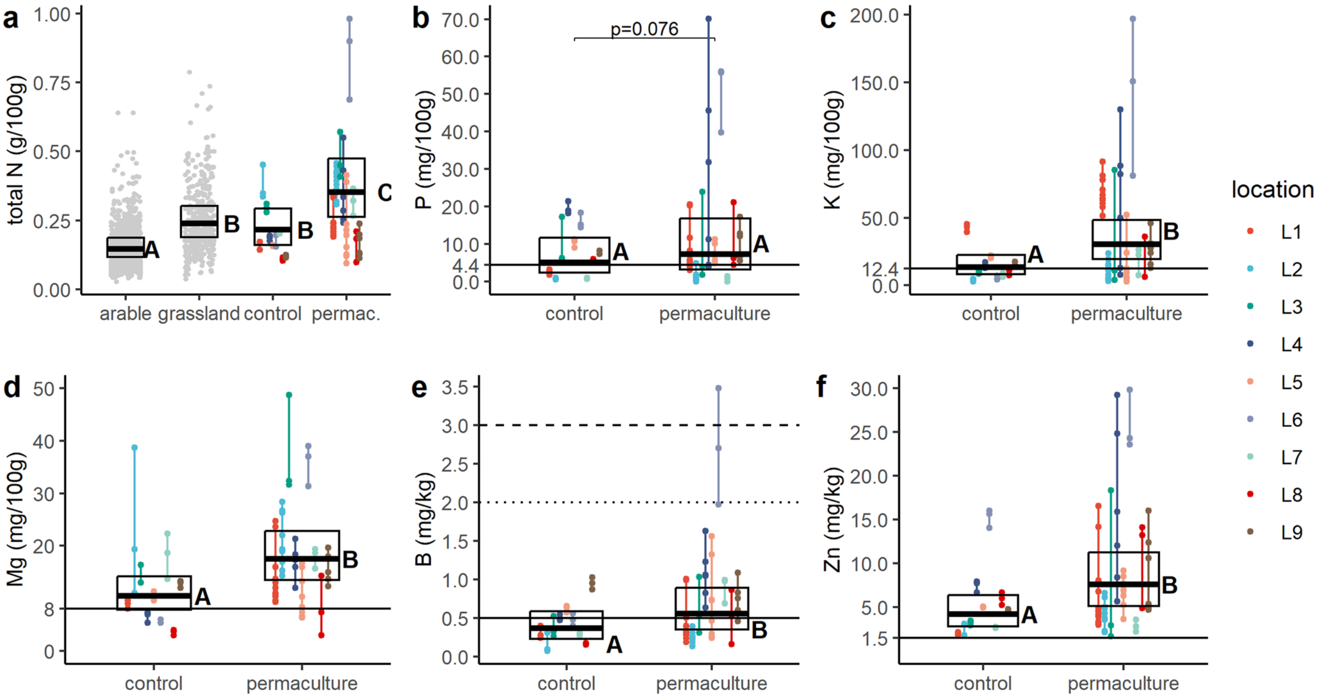

Fig. 2 | Soil macro- and micronutrients. a Topsoil (30 cm) total nitrogen content on nine permaculture sites, direct control fields of locally predominant agriculture and German grassland ($n = 387$) and arable land ($n = 1683$)[36]. Topsoil (30 cm) plant available phosphorus (**b**), potassium (**c**), magnesium (**d**), boron (**e**), and zinc (**f**) concentrations on nine permaculture sites and direct control fields of locally predominant agriculture. **b**–**d** solid line indicates lowest aspirational concentration in soils with medium soil texture in Germany[37]. **e** Solid line represents soil boron plant deficiency level[38,39] and dotted and dashed lines represent different suggested soil boron plant toxicity thresholds[38,40]. **f** Solid line represents soil zinc plant deficiency level[41,42]. Dots indicate individual data points. Colors indicate sampling pair locations. Crossbars indicate model-predicted mean and 95% confidence interval. Treatments not sharing the same letters are significantly different. Non-significant p values < 0.1 are written in the plot.

The second category is the promotion of biodiversity for the provisioning of ecosystem services. An important part of permaculture cultivation has been the utilization of semi-natural habitats to increase pollination and pest control, such as wildflower strips, ponds, more specialized habitats to support reptiles or amphibians, and extensively managed grassland.

The third category is the restoration of soil fertility, where manual labor is preferred over mechanized work in vegetable production. Market Gardening or bio-intensive mini-farming with dense and highly diverse crop cultures, a high degree of manual labor, minimum tillage, and permanent soil cover with straw or compost was mainly used for vegetable production. Similar to that, Hugelkultur, an extensive version of high permanent raised beds with a core of organic material, was used to further improve soil fertility, mitigate the effects of waterlogging, and recycle organic waste generated on the farm. A variation of holistic grazing management, which mimics the pattern of densely packed and constantly moving herds of wild grazing animals, was implemented with laying hens to improve soil and grassland quality.

However, it should be stressed that permaculture should not be reduced to a specific set of practices but also involves the conscious arrangement of context-specific land use practices and general management based on precise sustainability ethics.

Discussion

The results of this study highlight that permaculture in Central Europe enables higher carbon stocks, soil quality and biodiversity compared to predominant agriculture. Soil carbon stocks in the first 30 cm of topsoil on permaculture sites were comparable to average German grasslands while still producing cereals, vegetables, and fruit. In Germany, grasslands have on average a higher organic carbon content in the topsoil than even forests[38]. Deeper humic topsoil layers on permaculture sites indicate that the increase in total soil organic carbon exceeds the difference in carbon stocks observed in the first 30 cm of soil. Our estimate shows that permaculture with a mean soil carbon sequestration of 0.8 t ha^{-1} $year^{-1}$ could exceed the average sequestration rate of 0.6 t ha^{-1} $year^{-1}$ proposed by the "4 per 1000" initiative launched as a result of the 2015 United Nations Climate Change Conference[5]. While this estimate depends on assumptions, it may still be underestimated as the higher depth of humic topsoil on permaculture sites was not taken into account. In contrast, average net carbon losses have been observed for the predominant industrial agriculture in the past[39] and are predicted for the future[40]. We assume that the increased carbon stocks on permaculture sites are the result of a combination of various different practices. The carbon input is increased by the application of organic matter in the form of compost, livestock manure, organic mulch, or terra preta[41]. Here, it should be noted that overall carbon sequestration may be lower if part of this organic matter originates from outside the permaculture site and would otherwise have been stored in soils elsewhere. Carbon losses due to CO_2 emissions and topsoil erosion were not investigated in this study but are likely to be reduced in permaculture through permanent soil cover, reduced or no tillage, agroforestry, and decreased soil compaction[42].

We also found higher total nitrogen contents on permaculture sites. On the one hand, higher nitrogen contents promote plant productivity, but on the other hand, this means an increased risk of gaseous losses, e.g., nitrous oxide or ammonia into the atmosphere or nitrate leaching into groundwater[43]. As permaculture farms work with minimal or no tillage, permanent soil cover, and without mineral nitrogen fertilizers, it can be assumed that the risk of nitrogen losses is low[43]. A higher C/N ratio on permaculture sites is a limiting factor for the mineralization rate of nitrogen from organic inputs, while higher carbon and nitrogen levels, as well as higher microbial biomass, facilitate mineralization[44]. There was a trend towards a higher ratio of Gram-positive to Gram-negative bacteria on permaculture sites, indicating a higher proportion of more complex and recalcitrant carbon sources from soil organic matter[45]. However, as the nitrogen and carbon cycles in soil are complex, more detailed investigations

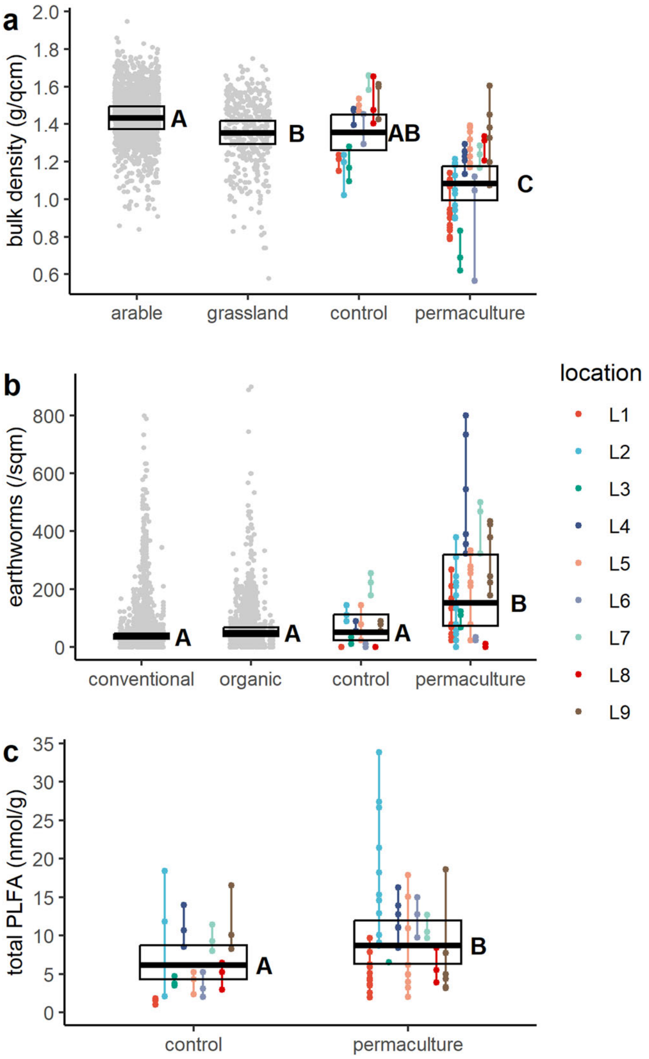

Fig. 3 | Soil biological and physical parameters. **a** Soil bulk density at 10–30 cm depth on nine permaculture sites, direct control fields of locally predominant agriculture and German grassland ($n = 387$) and arable land ($n = 1683$)[36]. **b** Earthworm abundance in the top 20 cm on nine permaculture sites, direct control fields of locally predominant agriculture, and European organic ($n = 60$) and conventional ($n = 77$) farms[35]. **c** Total microbial phospholipid fatty acid concentration in the top 10 cm on nine permaculture sites and direct control fields of locally predominant agriculture. Dots indicate individual data points. Colors indicate sampling pair locations and gray dots indicate data points of literature data. Crossbars indicate the model-predicted mean and 95% confidence interval. Treatments not sharing any same letters are significantly different.

are needed to make reliable statements on actual dynamics in and possible losses from permaculture sites.

The plant-extractable concentrations of soil phosphorous, potassium, magnesium, boron, and zinc were higher on permaculture sites than on conventionally fertilized soils of the control fields, which can be explained by a higher input of organic matter. These increases, which lead to improved contents with regard to plant deficiency thresholds (Fig. 3), indicate a higher soil quality in terms of plant nutrient supply. This is particularly important for phosphorous, as the permaculture sites worked according to organic farming standards and were, therefore, able to achieve high soil fertility without applying limited mineral resources. Still, one permaculture site with possibly plant-toxic soil boron levels suggests that organic nutrient inputs should also be handled with caution. Higher plant-extractable soil zinc concentrations, leading to increased contents in crops, are important to combat widespread zinc malnutrition in humans[46]. In line with our results, a case study on a permaculture farm in France found higher concentrations of soil carbon and bioavailable nutrients compared to pasture and arable agriculture[47].

A high input of organic matter together with minimal or no tillage is probably responsible for lower soil bulk densities[48,49] and increased abundances and diversity of earthworms on permaculture sites[50]. Soil bulk density is a key soil quality indicator with respect to plant root penetration, aeration, and infiltration and hereby codetermines erosion potential[51,52]. An increased earthworm abundance facilitates a reduced soil bulk density and vice versa[53]. Earthworms improve soil nutrient cycling, structural stability, and soil porosity, reduce run-off[32,50], and can even suppress crop pathogens[54,55]. A recent meta-analysis has shown that earthworms substantially increase crop yield by releasing nitrogen from organic matter, making them crucial for farmers who do not use mineral nitrogen fertilizers[56]. Mineral nitrogen fertilization directly promotes methane and nitrous oxide emissions from the soil, and the corresponding production process is one of the main contributors to greenhouse gas emissions from the agricultural system[57]. Earthworms are proposed as key indicators of soil biodiversity[50], which is recognized by both the Convention on Biological Diversity[58] and the European Commission[59] as essential for ecosystem functioning and the provision of soil services to humans.

Greater plant diversity increases rhizosphere carbon inputs to the microbial community leading to an increased microbial biomass and activity as well as soil carbon stocks, both of which have been found on permaculture sites[60]. More diverse vegetation also favors earthworms by providing nutritionally higher-quality root-derived carbon resources[61,62]. Vascular plants are the essential primary producers in agricultural systems, as well as a key resource for functionally important taxa of pollinators and natural pest enemies[31]. Avoiding the use of herbicides, focusing on mixed cropping, integrating herbaceous and woody crops, and small-scale cultivated areas could be the reasons for the strong increase in plant diversity on permaculture sites. Vascular plant diversity has been shown to be a good indicator of overall biodiversity[63], and there is consistently strong evidence that strategically increasing plant diversity increases crop and forage yield, yield stability, pollinators, weed suppression, and pest suppression[64]. We also found a substantially higher proportion of the land with trees on permaculture sites. Trees are an effective habitat indicator for overall species richness in agricultural landscapes[34] while increasing the abundance of pollinators and natural enemies[65]. Establishing trees is also one of the most important climate change mitigation measures on agricultural land[66] and could also mitigate other negative impacts of the conversion of forest biomes to agricultural land in the past and present[1]. The increases in plant species richness and tree habitats could be an explanation for the higher bird species richness on permaculture sites, as farmland bird biodiversity is closely related to semi-natural habitats[63]. Apart from their great importance as a flagship group for biodiversity conservation, farmland birds play an important role in insect pest control and weed suppression but are also responsible for potential crop damage[67].

Variability and land use history of permaculture sites

The variance of some variables assessed on permaculture sites was much higher compared to control sites. As permaculture is a very context-specific design tool, the differences between permaculture systems can be high. We assume that the variance between permaculture sites is the result of a combination of different factors, such as the degree of complexity, the intensity of land use, the level of implementation of permaculture principles, and the experience of the farmers. The degree of complexity varied between permaculture sites, for example, in the level of spatial and temporal integration of different land use practices, from mixed culture of vegetables to agroforestry and the integration of different types of livestock.

Given that the previous land use on the permaculture sites was, in most cases, similar to the land use on the control fields, it is unlikely that the land use history significantly contributes to the observed differences in biodiversity, soil quality, and carbon stocks. In three out of nine permaculture sites, part of the area had a history of grassland use. This may have contributed to the improved soil quality parameters compared to an arable

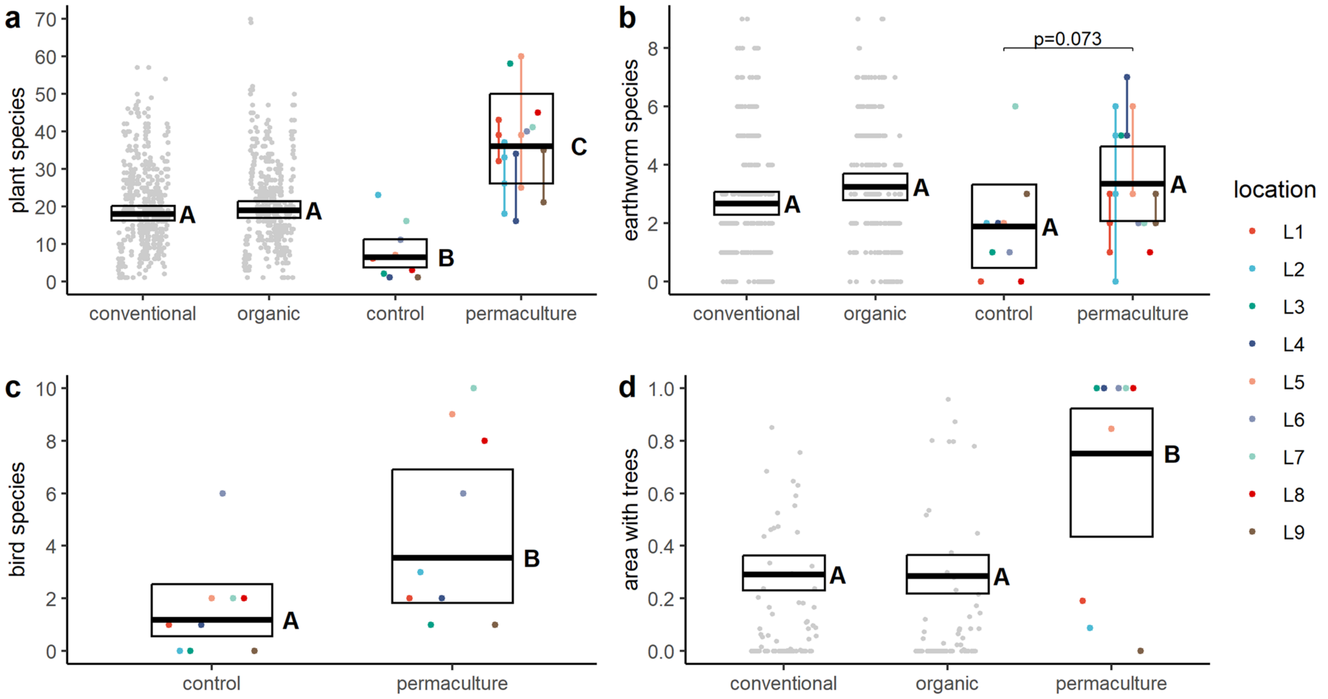

Fig. 4 | Biodiversity indicators. a Vascular plant species richness on $100\ m^2$ for nine permaculture sites, direct control fields of locally predominant agriculture and European organic ($n = 68$) and conventional ($n = 79$) farms[35]. **b** Earthworm species richness on $0.27\ m^2$ for nine permaculture sites, direct control fields of locally predominant agriculture, and European organic ($n = 60$) and conventional ($n = 77$) farms[35]. **c** Bird species richness based on songs recorded within around 70 m from the middle of nine permaculture sites and direct control fields of locally predominant agriculture. **d** Proportion of area with trees on nine permaculture sites and European organic ($n = 68$) and conventional ($n = 79$) farms[35]. This farm-level indicator is not compared to control fields that did not include trees in any case. Dots indicate individual data points. Colors indicate sampling pair locations and gray dots indicate data points of literature data. Crossbars indicate model-predicted mean and 95% confidence interval. Treatments not sharing the same letters are significantly different. Non-significant p values < 0.1 are written in the plot.

control field. However, it is more likely that other factors related to the permaculture practices and management itself are responsible for the observed differences, as the results for most assessed parameters were consistent at all permaculture sites. In contrast, different land use histories may have contributed to the high variance between permaculture sites.

Comparison with individual practices

We found that permaculture farms in Germany and Luxembourg tend to be rather small and young, which is similar to US permaculture farms[68]. Small farm sizes are favored by a low level of mechanization in combination with recent farm establishment[68]. The permaculture farms in this study relied exclusively on some form of direct marketing model. This reflects a higher level of consumer integration in food production and the possibility of obtaining sufficiently high prices for agricultural products. Permaculture farmers applied various practices to promote agroecosystem self-regulation by increasing carbon stocks, soil quality and biodiversity (Table 1). Our findings clearly show that permaculture farmers' intentions to change crucial ecosystem properties are successful. The most common practices applied on permaculture sites in this study were agroforestry, crop-livestock integration, market gardening, and facilitation of semi-natural habitats (Table 1). These practices are also associated with agroecology[24,25]. As there are no studies on whole commercial farms and temperate regions for agroecology[30], the most important variables are discussed in relation to agroforestry, crop-livestock integration, and facilitation of semi-natural habitats. As there are few studies on market gardening[69], the application of compost mulch is discussed as one of its key elements[70].

Table 1 | Summary of main permaculture practices utilized on permaculture sites in this study

Permaculture practice	Number of farms	Farms [ID]
Agroforestry	8	L1, L2, L3, L4, L5, L6, L7, L8
Crop-livestock integration	6	L1, L2, L4, L5, L7, L9
Market gardening	6	L1, L2, L4, L6, L8, L9
Wildflower strips	6	L1, L2, L4, L5, L6, L8
Ponds	5	L1, L2, L3, L5, L6
Additional semi-natural habitats	5	L2, L3, L5, L6, L8
Extensive grassland management	3	L1, L2, L7
Holistic grazing management	2	L4, L9
Hugelkultur	2	L3, L5

Permaculture sites had 27% higher soil carbon stocks and 71% higher soil carbon content. A meta-analysis found that carbon stocks are 19% higher in agroforestry systems worldwide, with the increase being slightly higher in subtropical climates than in temperate and tropical climates[71]. Soil organic carbon stocks in the top 30 cm of soil were 1% to 8% higher on four silvoarable agroforestry systems compared to control plots in France[72]. Soil carbon content was 27% higher for integrated crop-livestock versus only crop systems in Texas, USA[73]. No differences in soil carbon content were found between only crop and only pasture systems versus crop-livestock integration in Illinois, USA[74], nor in soil carbon stocks between only crop versus crop-livestock integration in the Pampas of Argentina[75]. It is difficult to estimate the effect of integrating semi-natural habitats into agricultural areas on soil carbon, especially when semi-natural habitats are not directly measured, as in this study. However, a review found a positive effect of semi-natural habitats on soil carbon in 17 out of 19 studies[76]. A global meta-analysis on land use change found that soil organic carbon stocks increase by 19% when cropland is converted to pasture and by 54% when cropland is converted to secondary forest[77]. Repeated application of compost mulch was found to increase soil carbon content by ~40% to 120%[78–80].

In this study, permaculture sites were found to have 20% lower soil bulk density. No significant difference in soil bulk density was found on six silvoarable and silvopastoral agroforestry sites compared to control plots in France[72]. A 1% lower soil bulk density was found on silvopastoral and agrosilvopastoral systems compared to continuous cropping in semi-arid climate in Brazil[81]. A 7% increase in soil bulk density was found both for crop-livestock integration in perennial pasture and in arable crop rotation compared to continuous cropping in Texas, USA[82]. In Georgia, USA, no effect of crop-livestock integration on soil bulk density was found for different tillage treatments[83]. Also, no difference in soil bulk density was found between semi-natural grasslands and apple orchards in Belgium[84] and between semi-natural habitats and field margins in Ontario, Canada[85]. In contrast, repeated application of compost mulch on agricultural soils reduced soil bulk density by 13% in California, USA[86], and by 9% in Wisconsin, USA[87].

Plant species richness was 457% higher on permaculture sites than on control fields. Two meta-analyses on European agroforestry systems found no significant effect on plant biodiversity[88,89]. There are no clear results on the effect of crop-livestock integration on plant species richness. However, the integration of livestock in a cover crop and soybean rotation in Rio Grande do Sul, Brazil, led to an increase in weed species richness by ~110%[90]. The proportion of semi-natural habitats on farmland had no effect on plant species richness in France[91]. In contrast, a global meta-analysis showed, that ecological restoration, often through the facilitation of semi-natural habitats, increased plant biodiversity by ~60%[92]. Compost application on grasslands in California, USA, had no effect on plant species richness[93].

Taken together, the results on isolated agroecological practices do not fully explain the strong effects of permaculture on carbon stocks, soil quality and biodiversity found in this study. The holistic systems approach of permaculture takes into account the interconnections and interdependencies between various elements of an agroecosystem[17,23], which could explain the advantages over isolated practices[94]. Complementary effects could compensate for the limitations or trade-offs of individual practices[95], while additive or even synergistic effects may explain a stronger response compared to individual practices[96]. In addition, the combination of various different practices might also increase the resilience and adaptability of the agricultural system[97].

Conclusion

In this study, we observed strong increases in soil carbon stocks, soil quality, and biodiversity through the use of permaculture. These results suggest that permaculture could contribute to the urgently needed transformation of agriculture to mitigate negative effects on various Earth system processes such as climate change, biogeochemical nitrogen and phosphorous flows, biosphere integrity, land-system change, and soil degradation[98,99]. Our results suggest that permaculture is an effective tool to promote sustainable agriculture (SDG 2), ensure sustainable production patterns (SDG 12), combat climate change (SDG 13) and halt and reverse land degradation and biodiversity loss (SDG 15)[100]. While there are numerous scientific results on more environmentally friendly practices such as agroforestry, crop-livestock integration, or the promotion of semi-natural habitats, the key capability of permaculture is to select, combine, and arrange precise practices for a specific context of land and farmer to create synergistic, regenerative and resilient agroecosystems. We see this as the missing link between scientific knowledge and implementation in practice. Therefore, we propose to foster the education of farmers and specialized consultants in permaculture design and related practices, as well as the redesign of agricultural systems according to permaculture principles. As the number of permaculture sites we were able to evaluate was still small and the variance between them was high, we also suggest further research on larger numbers of permaculture sites in different climates to provide evidence on more detailed processes. We are suggesting four major research questions: First, which variables, such as adopted practices, land use type(s), system complexity, crop productivity, and level of mechanization, determine the environmental effects of permaculture, and to which extent? Second, how strong are the synergistic or interactive effects of multiple integrated practices and land use types? Third, what are the pathways of nutrients and organic carbon, to, on, and from permaculture sites? And finally, what is the crop yield potential of permaculture systems in comparison to predominant industrial agriculture? We hope that answering these questions can promote wider adoption of permaculture and agroecology, enabling future agriculture to enhance its sustainability.

Materials and methods

Study sites

The study was conducted in Germany and Luxembourg in 2019, 2020, and 2021. In this area, nine permaculture sites were selected, constituting either a whole farm or part of a farm. Three criteria were used for selection. First, permaculture sites had to be designed and managed with permaculture, according to the farmer. Second, this agroecological production had to pay for itself, not being financed by other incomes of the farm. Third, at least two different land use practices had to be integrated into the agroecological production, either in the same area (e.g., tree crops and vegetables), temporally (e.g., livestock on crop areas), or indirectly (e.g., transfer of biomass). This criterion was included to recognize the principle of permaculture on creating synergies through the integration of various land use practices. We included all permaculture sites we could find that fit our criteria and were willing to participate. Due to the Covid-19 pandemic, we were limited to Germany starting from 2020.

At each permaculture site, one field of each land use type (e.g., vegetables, arable crops, tree crops, grassland, grazed land) was randomly selected to be sampled (called sampling plot). Permaculture sites with corresponding land use types, determining the number of sampling plots for each permaculture site, are listed in Table 2. Minimum area for individual field elements to be considered for sampling was 400 m^2 to fit the selection procedure of the study, whose data we used for comparison[35,101]. Areas of field elements were determined using QGIS 3.28.2. Only true agricultural areas were measured, all pathways broader than 30 cm (small footpaths between vegetable beds) were excluded. For each permaculture site, one control field with a locally predominant agricultural land use type was selected no further than three kilometers to ensure comparable climatic and geological conditions. In most cases, land use of control fields equaled previous land use on permaculture sites (Table 2). Locally predominant agricultural land use type was determined based on farmers interviews and supported by evaluation of aerial images five kilometers around the permaculture site using QGIS 3.28.2. Land use history of permaculture sites is reported in Table 2 and equalled land use of control fields for six out of nine cases.

Sampling was done between mid of May and beginning of June to ensure enough moisture for earthworm sampling as well as sufficient vegetation development for assessment of plant diversity. Each sampling was done within the same two days for each pair of permaculture site and control field.

Interview of farmers

Farmers were asked about farm area, permaculture site age, marketing strategies of agricultural produce, additional incomes, if working according to guidelines of organic agriculture (with or without certification), and which permaculture practices they use and why. Farmers of both permaculture sites and control fields were asked about predominant regional agricultural land use type and land use history of sampled fields (Table 2).

Soil sampling

At each sampling plot, soil samples were taken at three sampling points, being 10 m apart from each other and 20 m from the border of the field, if possible. In the case of raised beds or Hugelkultur, one sample each was taken from the center of the bed, the border to a footpath separating beds and the middle in between. At each sampling point, samples were taken from two depths, 0–10 cm, and 10–30 cm. The soil samples of 0–10 cm depth were stored at 6 °C, a subsample was freeze-dried within 24 hours for at least 36 hours and stored at −20 °C for later analysis of PLFA. At each

Table 2 | Characteristics of investigated permaculture (PC) sites

location ID	farm area [ha]	PC site area [ha]	PC site age [a]	Land use type	Area [ha]	Detail	Previous land use	Control field
L1	14	10.4	11	arable	2.0	fodder crops	arable (>30 a)	wheat (arable, >50 a)
				grassland	1.8	laying hens, hay production	arable (>30 a)	
				grazing	5.7	sheep, cattle, fruit trees	arable (>30 a)	
				vegetables	0.9	vegetables	arable (>30 a)	
L2	10	1.7	10	arable	0.9	pigs, grains, fodder crops	grassland (>50 a)	mowing meadow (grassland, >50 a)
				grassland	0.5	hay production	grassland (>50 a)	
				grazing	0.1	geese, fruit trees	grassland (>50 a)	
				vegetables	0.2	vegetables	grassland (>50 a)	
L3	3.6	0.8	10	vegetables	0.8	vegetables, fruit trees	arable (>10 a)	wheat (arable, >20 a)
L4	2.5	0.9	4	grazing	0.7	laying hens, fruit trees	Streuobst (>15 a)	wheat (arable, >20 a)
				vegetables	0.2	vegetables, fruit trees, berry bushes	arable (>15 a)	
L5	10	3.1	8	arable	0.4	pigs, root crops	industrial (>50 a)	fodder beet (arable, >50 a)
				grazing	2.6	sheep, fruit trees	grassland (>10 a)	
				vegetables	0.1	vegetables	industrial (>50 a)	
L6	1.5	1.0	5	vegetables	1.0	vegetables, fruit trees, berry bushes	Streuobst (>10 a)	vegetables (vegetables, >50 a)
L7	80	2.6	20	grazing	2.6	cattle, fruit trees	grassland (>10 a)	hayfield (grassland, >50 a)
L8	1	0.9	11	vegetables	0.9	vegetables, fruit trees, berry bushes	arable (>10 a)	wheat (arable, >50 a)
L9	2	1.8	3	grazing	1.4	laying hens	arable (>20 a)	wheat (arable, >20 a)
				vegetables	0.4	vegetables	arable (>20 a)	

Land use history of control fields is given in parentheses.

sampling point an undisturbed soil sample was taken with a soil sampling ring ($d = 5$ cm, $h = 5$ cm) from the middle of each sampling depth (ca. 5 and 20 cm) to determine soil bulk density and water content. Therefore samples were stored airtight, weighted in field-wet condition, dried at 95 °C for at least 24 hours, and weighted again.

At each sampling point the depth of the humic topsoil layer was determined with a „Pürckhauer" soil sampler up to 1 m deep. Depths of >1 m were taken as 1 m for data analysis.

Earthworm sampling

At each soil sampling point a soil core of 30 cm × 30 cm × 20 cm deep was taken out and hand sorted for earthworms for 20 minutes by one person. This sampling procedure was based on the approach of ref. 35, to allow for comparability with this dataset. In contrast to the approach of ref. 35 no extraction solution was applied to the ground. Earthworms were preserved in 70% ethanol for later determination in the lab. Earthworms were determined to species level, if possible.

Vegetation sampling

At each sampling plot, a square plot of 100 m^2 was set up with a distance of at least 20 m from the borders of the field, if possible. All vascular plants within the square plot were determined to species level, to determine species richness. It was recorded if the tree cover of the sampling plot was higher than 1%. This sampling procedure was based on the approach of ref. 35, to allow for comparability with this dataset.

Bird recording

At each permaculture site and control field, one audio recorder (AudioMoth) was deployed. The audio recorders were positioned in the middle of the site area or control field and at similar distances (at least 80 m) to natural habitats (tree rows, hedges, forests) for each pair of farm and control fields. Bird calls were recorded three times for 10 minutes each: around sunrise, one hour after sunrise, and around sunset[102]. For each pair of farm and control fields, bird calls were recorded on the same day. Sampling days were selected according to weather conditions (no rain, no strong wind).

All audio recordings were resampled at 22,050 Hz in order to improve frequency resolution[103]. In each recording all species present were identified aurally and visually. With the help of the software Audacity (version 5.4.8), a 1024-point Hann window spectrogram showed frequency variations over time. Species identifications were verified using the databases Xeno-canto (xeno-canto.org), e-bird (ebird.org), and Tierstimmenarchiv (tierstimmenarchiv.de). Songs or calls that could not be identified to species level were not included in further analysis. For each bird individual the maximal relative should level was measured in decibels (dB) and its associated frequency in Hertz (Hz) using the software Kaleidoscope Pro (version 5.4.8). The maximal relative sound level was measured by selecting the area around the loudest song or call in the recording. It was used as an indicator for the distance of the respective bird individuals from the recorder[104]. To exclude birds located outside the permaculture site, only songs or calls above −35 dB were included, since this loudness is typically shown by species singing no further than 70 m of the recorder (Manon Edo, unpublished data).

Soil analysis

Soil laboratory analysis was done by the Agricultural Research Institute Speyer, Germany (LUFA Speyer). Extraction and analysis procedure followed the methods in the manual of the Association of German Agricultural Research Institutes (VDLUFA)[105]. In the following, corresponding chapters with detailed approaches are given in parentheses.

Soil pH was determined by electrometric measurement of H+ ion activity in CaCl2 solution (A 5.1.1). Dumas combustion method was used to determine soil organic carbon (A 4.1.3.1) and total nitrogen (A 2.2.5). Phosphate and potassium oxide were extracted with calcium-acetate-lactate solution (CAL) and determined by photometric measurement (A 6.2.1.1). Magnesium was extracted with calcium chloride solution and measured with optical emission spectrometry (ICP-OES) (A 6.2.4.1). Boron, copper, manganese, and zinc were extracted with calcium chloride and DTPA

Table 3 | Results of statistical evaluation of each response variable

Response variable	Distribution family	Explanatory variable (fixed)	χ^2 value	Residual df	p value	Random factors
Bird species richness	genpois	management	14.10	14	**<0.001**	location
Earthworm abundance	nbinom1	management	40.80	2267	**<0.001**	location
Earthworm species richness	gaussian	management	9.30	759	**0.026**	location
Plant species richness	genpois	management	52.38	843	**<0.001**	location
Tree area	ordbeta	management	8.47	149	**0.014**	location
pH-value	gaussian	management	0.36	80	0.55	location, texture class
Gravimetric moisture	ordbeta	management	42.89	77	**<0.001**	location, texture class
Volumetric moisture	ordbeta	management	3.42	77	*0.064*	location, texture class
Humic topsoil depth	nbinom2	management	48.81	79	**<0.001**	location, texture class
Bulk density	gaussian	management	244.7	2147	**<0.001**	location, texture class
Organic C content	gaussian	management	506.5	2147	**<0.001**	location, texture class
Organic C stock	nbinom2	management	355.4	2147	**<0.001**	location, texture class
Organic C stock	gaussian	permaculture age	4.36	52	**0.037**	location, texture class
Total N	nbinom2	management	662.2	2147	**<0.001**	location, texture class
P	nbinom2	management	3.15	78	*0.076*	location, texture class, pH
K	nbinom2	management	21.15	78	**<0.001**	location, texture class, pH
Mg	genpois	management	24.58	78	**<0.001**	location, texture class, pH
B	tweedie	management	8.60	77	**0.003**	location, texture class, pH
Cu	gaussian	management	0.10	78	0.750	location, texture class, pH
Mn	gaussian	management	0.70	78	0.404	location, texture class, pH
Zn	genpois	management	31.48	78	**<0.001**	location, texture class, pH
Total PLFA	nbinom2	management	7.31	78	**0.007**	location, texture class, pH
Bacteria PLFA	genpois	management	9.92	78	**0.002**	location, texture class, pH
Fungi PLFA	nbinom2	management	3.89	78	**0.049**	location, texture class, pH
Fungi/bacteria PLFA ratio	gaussian	management	0.86	78	0.353	location, texture class, pH
Gram−/gram+ PLFA ratio	gaussian	management	2.77	78	*0.096*	location, texture class, pH
Mykorrhizae/fungi PLFA ratio	gaussian	management	0.62	71	0.430	location, texture class, pH

Structure of generalized linear mixed models fitted in R using the glmmTMB package. χ^2 values and p values were obtained by Type II Wald χ^2 tests on model outcomes. Significant p values are highlighted in bold, and statistical trends are in italics.

solution (CAT) and measured with ICP-OES (A 6.4.1). Values below the detection threshold were taken as zero. For soil variables, a weighted mean was calculated for samples from the two sampling horizons to obtain a value for the first 30 cm of topsoil. For soil type comparison, samples were classified manually "by feel" by well-trained and experienced laboratory staff into seven soil texture classes with decreasing particle size (D 2.1)[106].

Soil organic carbon stocks were calculated as soil organic carbon concentration multiplied by bulk density and horizon depth (30 cm). Values for soil phosphate and potassium oxide concentrations were converted to phosphorus and potassium concentrations using respective molar masses.

Abundance and structure of soil microbial communities

To investigate the microbial community, PLFA was analyzed in soil samples. The extraction procedure followed the method by Bligh and Dyer[107] and White et al.[108] with small modifications by Kenngott et al.[109]. Phospholipids were extracted from 2 g of freeze-dried soil using a mixture of 2 mL chloroform, 4 mL methanol, and 1.6 mL phosphate buffer as extraction solution. Extracts were agitated for 1 h in an overhead shaker (16 rpm). Then, phospholipids were separated from the neutral lipids and glycolipids using solid-phase extraction cleanup (Chromabond, Macherey-Nagel, Düren, Germany). Eluted PLFAs were transesterified with a 0.25 molar solution of methanolic trimethylsulfonium hydroxide[110]. The extracts were analyzed via GC-FID (Varian CP-3800, Varian, Darmstadt, Germany). Quantification was based on external calibration with reference standards. The PLFA used as quantitative standards and as biomarkers for soil microbial community groups were: i15:0 and i17:0 for gram-postive bacteria, 16:1ω7c and 18:1ω9c for gram-negative bacteria[111,112], 16:1ω5c for arbuscular mycorrhizal fungi[113,114], 18:2ω6c for saprophytic fungi[112,115,116] and 20:4ω6c for protozoa[117,118]. To compensate for differences in mass weight of individual biomarkers, molar concentrations per gram of soil dry matter were used. Total PLFA corresponds to the sum of individual PLFA biomarkers and is used as proxy for the total viable microbial biomass[119]. For evaluation of specific groups (bacteria, fungi, etc.) corresponding biomarkers were summed up as well. Changes in the chemotaxonomic structure of microbial communities were evaluated using the fungi-to-bacteria, the arbuscular mycorrhizal-to-saprophytic fungi, and the gram-positive to-gram-negative bacteria ratios.

Additional data

The data of Lüscher et al.[35] was used for additional comparison of biodiversity variables. Here, the dataset is published as supplementary information to the respective article (https://doi.org/10.1890/15-1985.1)[35]. From this dataset, all European regions with either arable crops, grassland, horticulture, or mixed culture were selected. Special land use types like olives or vineyards were omitted. For comparability with this study only areal plots were used for evaluation. As in this study, only fully determined earthworm species were counted for species richness comparison. For each farm, including permaculture sites from this study, the share of the area with tree cover was calculated. For statistical analysis, the farm ID of this additional biodiversity dataset was treated as a location variable from this study and management (conventional or organic) as a management variable from this study (permaculture, control).

Table 4 | Results of post hoc comparisons

Response variable	Pairwise comparison		*z/t* value	*p* value
Earthworm abundance	permaculture	control	5.46	**<0.001**
	permaculture	conventional	3.69	**0.001**
	permaculture	organic	2.78	**0.028**
	control	conventional	0.84	0.833
	control	organic	0.03	1.000
	conventional	organic	1.78	0.285
Earthworm species richness	permaculture	control	2.43	*0.073*
	permaculture	conventional	0.98	0.762
	permaculture	organic	0.16	0.999
	control	conventional	1.04	0.728
	control	organic	1.77	0.291
	conventional	organic	1.84	0.256
Plant species richness	permaculture	control	6.66	**<0.001**
	permaculture	conventional	3.96	**<0.001**
	permaculture	organic	3.65	**0.002**
	control	conventional	3.60	**0.002**
	control	organic	3.76	**0.001**
	conventional	organic	0.64	0.920
Tree area	permaculture	conventional	2.87	**0.011**
	permaculture	organic	2.89	**0.011**
	conventional	organic	0.14	0.990
Bulk density	permaculture	control	10.04	**<0.001**
	permaculture	arable	10.04	**<0.001**
	permaculture	grassland	7.63	**<0.001**
	control	arabe	2.08	0.159
	control	grassland	0.03	1.000
	arable	grassland	9.64	**<0.001**
Organic C content	permaculture	control	7.19	**<0.001**
	permaculture	arable	7.97	**<0.001**
	permaculture	grassland	2.41	*0.076*
	control	arabe	1.00	0.750
	control	grassland	3.84	**<0.001**
	arable	grassland	20.78	**<0.001**
Organic C stock	permaculture	control	4.60	**<0.001**
	permaculture	arable	3.26	**0.006**
	permaculture	grassland	0.40	0.978
	control	arabe	0.85	0.832
	control	grassland	2.64	**0.041**
	arable	grassland	18.19	**<0.001**
Total *N*	permaculture	control	8.34	**<0.001**
	permaculture	arable	9.30	**<0.001**
	permaculture	grassland	4.11	**<0.001**
	control	arabe	3.82	**<0.001**
	control	grassland	1.00	0.751
	arable	grassland	23.38	**<0.001**

Z/t values are given as absolute numbers. Significant *p* values are presented in bold font, while *p* values indicating a statistical trend are presented in italic font.

The data of Poeplau et al.[36] was used for additional comparison of soil variables. Here the dataset is published in the OpenAgrar repository (https://doi.org/10.3220/DATA20200203151139)[120]. From this dataset, all sites were selected that were sampled at depths of 0–10 cm and 10–30 cm, contained minerals soils (organic soils omitted), were sampled on cropland or on grassland (special permanent crops omitted) and values available for soil organic carbon, total nitrogen, and bulk density. Soil texture classes of this dataset were converted to the seven soil texture classes used in this study[105]. For statistical analysis, the point ID of this additional soil dataset was treated as a location variable from this study, and land use type (cropland or grassland) as a management variable from this study (permaculture, control).

Statistics

Statistical analysis was carried out using R (R 4.2.1, R Development Core Team 2022). For each response variable (Table 3) a generalized linear mixed model using the 'glmmTMB' package was fitted with management as fixed predictor variable[121]. The management variable comprises factor levels of permaculture and control field as well as organic and conventional agriculture or arable land and grassland in case of added literature datasets (see above). To account for the paired sampling design of permaculture sites and corresponding control fields, location was included as a random factor for each response variable. For soil-related response variables, soil texture class and pH value were included as random factors to account for possible differences in soil type. For organic carbon and total nitrogen levels, pH value was not included as these parameters do not depend on soil pH[122].

For organic carbon stocks, a second model was fitted with age as predictor variable and location and soil texture class as random factors to estimate carbon sequestration. To set today as a baseline, the age of the permaculture sites was set to zero, and the age of the paired control fields was set to the negative age of the corresponding permaculture site. This calculation was done only for six permaculture sites, where previous land use equalled land use of control fields. Further, this calculation is based on the assumption that the carbon level was originally sufficiently equal on-site pairs and did not change on control fields.

Response variables with percentage values that are limited to values between 0 and 1 were fitted, assuming a beta distribution (beta or ordbeta families). All other response variables were fitted subsequently assuming a normal (gaussian family), Poisson (companies or generous families), or negative binomial (nbinom1 or nbinom2 families) distribution, depending on model diagnostics. Residuals and diagnostics of models were checked using the 'DHARMa' package to control for model misspecification problems such as multicollinearity, over/underdispersion, zero-inflation residual, spatial, and temporal autocorrelation[123]. If more than one distribution family produced a model with acceptable diagnostics, we selected the model according to the Akaike Information Criterion[124]. If none of these families produced a model with acceptable diagnostics, we fitted another model assuming a Tweedie (Tweedie family) distribution and checked model diagnostics.

The significance of the predictor variable was evaluated with a Type II Wald χ^2 test using the Anova function of the 'car' package (Table 3)[125]. Post hoc pairwise comparisons of management factor levels were done with Tukey correction using the 'emmeans' package (Table 4)[126]. The ggpredict function of the 'ggeffects' package was used to compute model-predicted means and 95% confidence intervals[127].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data that supports the findings of this study is available in The Knowledge Network for Biocomplexity (KNB) with the identifier https://doi.org/10.5063/F1J964VN[128].

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Author contributions

Funding acquisition, sampling, visualization, and original draft preparation were done by Julius Reiff. Conceptualization and methodology development were done by Julius Reiff, Martin H. Entling, and Hermann F. Jungkunst. Analysis of phospholipid fatty-acids was done by Ken M. Mauser. Identification of earthworm species was done by Sophie Kampel and Johann G. Zaller. Identification of bird species by means of recorded songs and calls was done by Sophie Regending and Verena Rösch. All authors contributed to the review and editing.

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Chapter 4

Crop productivity of Central European Permaculture is within the range of organic and conventional agriculture.

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Crop productivity of Central European Permaculture is within the range of organic and conventional agriculture.

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Abstract

Permaculture is a promising framework to design and manage sustainable food production systems. However, there is still a lack of scientific evidence especially on the crop productivity of permaculture systems. In this first study on permaculture yield, we collected yield data of eleven permaculture sites, that work according to organic guidelines, in and around Germany. We used the Land Equivalent Ratio (LER) as index to compare mixed cropping systems of permaculture sites with average monoculture yield data of total and organic German agriculture. An LER of 1 indicates equal yields of the compared polyculture and monoculture. Mean permaculture LER as compared to total German agriculture was 0.80 ± 0.27 and 1.44 ± 0.52 as compared to German organic agriculture, both with no significant difference to 1. Our results imply, that yields of permaculture sites are comparable to predominant industrial agriculture and might even exceed the yields of organic agriculture. Provided that future studies will support our findings, permaculture could potentially bridge the productivity gap between organic and conventional agriculture. Most importantly, the variables that determine the difference in crop productivity need to be identified and evaluated.

Keywords: agroecology, permaculture, regenerative agriculture, sustainable agriculture, productivity, crop yield, land equivalent ratio

Introduction

Modern industrial agriculture, characterized by high chemical inputs, monocropping and intense soil cultivation, has led to environmental degradations such as soil erosion and loss of biodiversity [1–3]. In response to these challenges, alternative farming approaches, that prioritize ecological sustainability and regenerative practices are gaining increased attention, such as agroecology [4], regenerative agriculture [5] or

diversified farming systems [6]. A promising framework for the design and management of those food production systems is permaculture [7–9].

Permaculture is an agroecological design system that draws inspiration from natural ecosystems and traditional and indigenous farming practices [7]. It emphasizes the integration of a diversity of crops, with a focus on perennial and woody crops, and livestock to create self-sufficient and resilient agricultural systems [10]. By mimicking the patterns and relationships found in natural ecosystems, permaculture seeks to optimize resaource use, promote biodiversity and enhance ecosystem health [8]. Examples for these patterns are diverse polycultures, permanent soil cover, a focus on woody crops, the integration of crops and livestock as well as management of grazing animals in densely packed herds [9]. Amongst others, permaculture principles emphasize polycultures, agroforestry systems, crop-livestock integration, facilitation of semi-natural habitats to enhance pest control and pollination, as well as soil conservation techniques such as mulching, composting and no-till cultivation [11].

Implementing these principles, permaculture sites showed strong improvements in soil quality, soil carbon storage and biodiversity compared to predominant agriculture in Central Europe [11]. In addition, permaculture strives for a holistic approach that not only focuses on agricultural production but also considers social and economic aspects that aim for sustainable livelihoods and community resilience [12].

Although there is some evidence that permaculture can be an ecologically sustainable farming practice, there is a lack of scientific research on its crop productivity [10]. The few existing studies have focused only on economic performance [13], income diversity [14] or qualitative interviews of farmers [15]. Therefore, this study aims to evaluate the land productivity of permaculture sites by comparing their yields to those of predominant modern agriculture in Central Europe. We used the Land Equivalent Ratio (LER) as an established tool to evaluate the productivity of mixed crop permaculture sites [16]. The LER is widely used for situations with intercrops of no more than two species while evidence from combinations of three crops is scarce, with one study investigating a combination of seven crop species [17,18]. In this case, it was not feasible to conduct a single-crop experiment for every crop variety at each permaculture site. Mean values from larger samples were used to determine sole crop yields in some cases [19], or they were estimated from the intercropping experiment itself [20]. The approach of using maximum or average sole crop yields was also described by [21]. Therefore, we used national average yield data as sole crop yield values in this study. By quantifying and comparing the yields of permaculture sites with predominant industrial agricultural systems, we provide insights into the potential benefits and limitations of adopting this approach.

Materials and methods

Study sites

This study evaluates yield data from eleven commercial permaculture sites in Germany (Rhineland-Palatinate, Bavaria, North Rhine-Westphalia and Lower Saxony), Switzerland, and Luxembourg, which either constitute a farm or are part of a farm. (Tab. 1). Three criteria were used for site selection. First, permaculture sites had to be designed and managed with permaculture, according to the farmer. Second, we only investigated commercial permaculture sites to focus on food production systems and to exclude permaculture sites established mainly for other purposes like subsistence or education. Third, at least two different types of land use (e.g. grazing and fruit trees) had to be integrated at the agroecological production. We have considered all farms in Germany and the surrounding regions, that met the specified criteria and were willing and able to provide their yield data. This data represents the crop yields sold by the farms and was collected by the farms themselves. Yield datasets covered one year per farm between 2019 and 2022 and only crop yields from permaculture areas allocated mainly to crop production. Livestock yields were excluded, as the majority of livestock production in Central Europe is based on imported forage and therefore not directly comparable in terms of land requirements. Farms were rather young with a mean age of 6 years at investigation. Therefore areas dominated by newly planted berry bushes or fruit trees, not having reached full yield potential, were excluded from the evaluation. All farms followed the principles of organic agriculture, although not all were certified. Permaculture sites 2, 3, 6 and 8 were part of a separate study on soil quality, carbon storage and biodiversity of permaculture [11]. These sites share identical identifiers in both studies.

Table 1: Investigated Farms with permaculture. Only crop types written in italic were investigated in this study. The remaining crop types were excluded from the investigation as they were either newly planted woody crops, from areas primarily designated for livestock production, or from non-permaculture areas.

Site	Country	Establish-ment	Survey	Farm area [ha]	Investigated area [ha]	Farm plant production	Farm livestock
1	Switzerland	2011	2021	2,5	0,02	*vegetables*, *soft fruit*, tree crops, grassland	
2	Germany	2009	2019	10	0,44	*vegetables*, *soft fruit*, *tree crops*, grassland, grains	chicken, pigs, geese
3	Germany	2009	2019	3,6	0,66	*vegetables*, *soft fruit*, *tree crops*, grains	chicken
4	Switzerland	2020	2021	5	0,06	*vegetables*, soft fruit, tree crops, grassland	chicken, sheep
5	Germany	2019	2021	1,9	0,22	*vegetables*, soft fruit, tree crops	runner ducks, chicken
6	Luxembourg	2014	2020	1,5	1,01	*vegetables*, *soft fruit*, *tree crops*	runner ducks
7	Germany	2018	2021	3,5	1,60	*vegetables*, tree crops	
8	Germany	2013	2022	1,1	1,06	*vegetables*, soft fruit, tree crops	
9	Germany	2022	2022	0,4	0,06	*vegetables*, *soft fruit*, tree crops, grassland	sheep
10	Switzerland	2015	2021	3	0,32	*vegetables*, *soft fruit*, *tree crops*	
11	Germany	2017	2022	2,4	0,15	*vegetables*, soft fruit, tree crops, grassland	chicken, pigs, sheep

Reference data

To compare permaculture yields with predominant industrial agriculture, data by the Federal Statistical Office of Germany for German agriculture of respective years was used for vegetables and strawberries [22], potatoes [23], tree fruit [24], and other soft fruit [25]. These surveys are representative of Germany. Data was collected from 5,100 farms in 2019 and 2020, and from 4,500 farms in 2021 and 2022 (Federal Statistical Office Germany, 2024; personal communication). Throughout Germany, most arable land parcels are used for single crop cultivation [26]. These datasets included mean crop yield data of total German agriculture (Y_{tot_year}) and organic German agriculture (Y_{org_year}). For vegetable or fruit varieties that were not covered by these collections, mean values of respective vegetable group (such as legumes) or of all tree or soft fruit was were used for comparison (e.g. $\overline{Y}_{tot\_2022}$(cabbage vegetables) for Y_{site1_2022}(pak choi)). For organic production, vegetable yield values were only given for vegetable groups of root and tuber, fruit, leaf and stalk, cabbage and other vegetables as well as legumes (e.g. Y_{org_2022}(legumes)). Thus, a ratio of organic to total agriculture was calculated for each group and year (e.g. R_{2022}(legumes)=Y_{org_2022}(legumes)/Y_{tot_2022}(legumes)). To estimate the organic yield data of specific crop varieties, the total crop yield data of those varieties was multiplied by the respective total to organic vegetable group ratio (e.g. Y_{org_2022}(sugar pea)=Y_{tot_2022}(sugar pea)*R_{2022}(legumes)). To estimate organic potato yield, total yield was multiplied by organic to total root and tuber vegetable ratio (Y_{org_2022}(potato)=Y_{tot_2022}(potato)*R_{2022}(root and tuber vegetables)). For tree crops organic yield data was only available for 2022, so an organic to total ratio was calculated from this data (e.g. R_{2022}(apple)=Y_{org_2022}(apple)/Y_{tot_2022}(apple)) and applied to data of the other years (e.g. Y_{org_2019}(apple)=Y_{tot_2019}(apple)*R_{2022}(apple). Nut crops were only grown on one permaculture site and were a relatively small proportion of total production. (Tab. 2). Nut yield data of German agriculture was not available, therefore general literature values were used for comparison of walnut [27] and hazelnut [28] yields. Tree crop organic to total ratio was applied to estimate organic nut yield values (e.g. Y_{org_2022}(hazelnut)=$Y_{erdogan\_2018}$(hazelnut)*R_{2022}(tree crops).

Land Equivalent Ratio

In all cases, permaculture sites consisted of mixed cultures of different vegetable varieties and often additional fruit trees and berry bushes. Added integration of livestock was common, but resulting extra animal yields are not include-able in this study. The land equivalent ratio (LER) is used as an index to assess the relative productivity of these mixed crop systems compared to the mean sole crop productivity of total and organic German agriculture in the respective years [21,29–32]. The LER for a specific permaculture site *site* as compared to one of the management categories *man* (total or organic German agriculture) was calculated as follows

$$LER_{man,site}=\sum_{i=1}^{m}\frac{Y_{site}(i)}{Y_{man,year}(i)}$$

where m is the number of different crops yielded at the permaculture site, $Y_{man,year}(i)$ is the monocultural yield of the i^{th} crop of respective management and year and $Y_{site}(i)$ is the yield of the i^{th} crop under intercropping of the permaculture site. Two LER values were calculated for each permaculture site, one compared to total German agriculture and one compared to German organic agriculture. An LER of 1 indicates equal productivity of the permaculture mixed system and statistical data sole crops.

Statistics

Statistical analysis was carried out using R (R 4.2.1, R Development Core Team 2022). Both samples of LER values (compared to total or organic German agriculture) were checked for normal distribution visually using the function *qqplot()* as well as mathematically using a Shapiro-Wilk-Test with the function *shapiro.test()*. A one sample t-Test was used to test both groups of LER values against the specified value of 1 using the function *t.test()*.

Two linear models were calculated using the function *lm()* with total LER or organic LER values as response variables and age, investigated area and presence of livestock as predictor variables. Automated model selection was performed using the *dredge()* function. Model diagnostics to check for deviations from the model assumptions (normal distribution, homogeneity of variance, etc.) were performed visually using the *plot()* function on the linear model outputs. The significance of the predictor variables was evaluated with a Type II F-test using the Anova function of the 'car' package [33] on the full model, since no model with significant predictors was found (Table 2).

Values in the text are given as mean plus minus 0.95 confidence interval.

Results and Discussion

On average, the crop yield of permaculture sites was 21,8 ± 7,3 t ha^{-1}. Table 3 displays the total crop yield and proportions of different crop types for each permaculture site. Mean permaculture site LER as compared to total German agriculture was 0.80 ± 0.27 and 1.44 ± 0.52 as compared to organic German agriculture (Fig. 1, Tab. 2+3). The permaculture LER of 0.80 suggests that permaculture requires 20% more land to achieve the same yield as total German agriculture, resulting in 20% lower permaculture productivity. Consequently these results suggest a 44% higher permaculture productivity compared to organic German agriculture.

However, both mean LER values were not significantly different from 1, indicating no significant difference in permaculture productivity compared to average German agriculture. This indicates that yields of permaculture sites are comparable to predominant industrial agriculture. However, LER values varied strongly between individual permaculture sites. A recent meta study found a mean LER of 1.36 ± 0.04 with a similar range from 0.5 to 2.6 for intercropping of vegetables and/or fruit trees (Paut, 2018). This value corresponds to the permaculture LER of this study as compared to German organic agriculture in general, as the permaculture farms were operated according to organic farming guidelines. As the mean permaculture LER is substantially higher with 1.44 ± 0.52, its difference from 1 might therefore be largely explained by the use of intercropping.

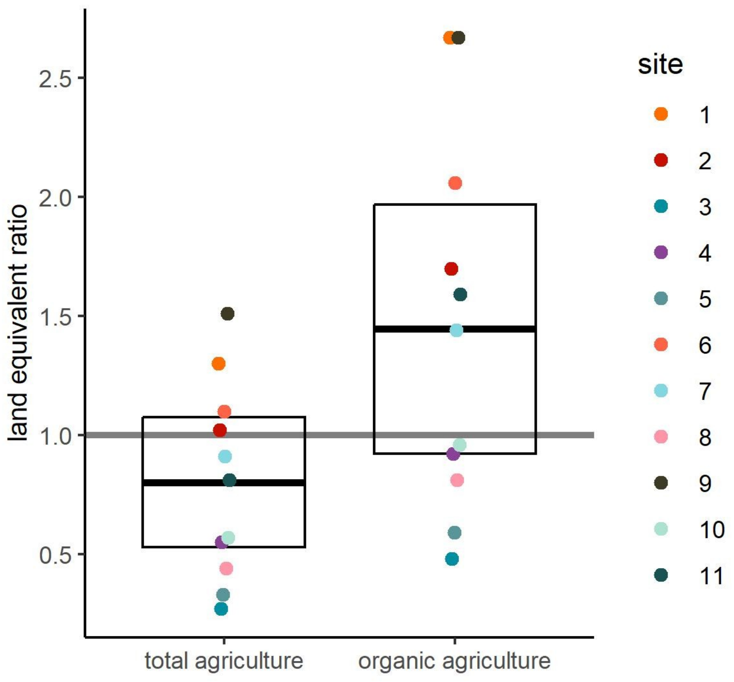

Figure 1: Land equivalent ratios (LER) of permaculture. LER's of eleven permaculture sites as compared to total (p=0.137, t=-1.62, df=10) and organic (p=0.087, t=1.98, df=10) German agriculture. Bars with error bars indicate mean and 95% confidence interval, coloured dots indicate individual data points and horizontal line indicates equal land requirement of permaculture and reference.

It is likely, that permaculture yields are even higher than reported in this study. At some permaculture sites, yields of soft fruits, tree fruits and nuts from areas with mainly vegetable production were not recorded by the farmers. Additionally, feed provisioning from investigated areas for livestock integrated in crop production could not be taken into account in this study. Such provision constitutes an additional yield produced within the same area, reducing the need for external feeds. This includes runner ducks or chicken for permanent or temporal pest control on vegetable areas, sheep, geese or chicken grazing below woody crops or pigs fed with crops not suitable for sale.

LER values as compared to total German agriculture and to German organic agriculture both were not significantly dependent on any of the tested predictor variables: farm age, investigated area and presence of livestock (Tab. 2). Nevertheless, the variability of the permaculture LER values was high. Permaculture is a very context specific design tool, thus every permaculture system is different. A high variance among permaculture sites was also found for increases in soil quality, carbon storage and biodiversity compared to predominant agriculture in Central Europe (Reiff et al., 2024). We assume that variance in permaculture LER's is a result of a combination of different factors such as the degree of complexity, the management intensity, the age of the system as well as the experience of the farmers. The degree of complexity varied among permaculture sites and could be determined by the level of spatial and temporal integration of different land use elements. This can range from the mixed cultivation of vegetables to agroforestry and the integration of different types of livestock. A recent experiment showed, that LER's of mixed culture of seven annual crops varied between 1.18 and 5.67 depending on cropping design (Deb, 2021). Also, the level of management intensity differed between permaculture sites, from more extensive systems with a stronger focus on nature conservation and input efficiency to more intensive systems with a higher input of labour and resources. Ultimately, the effectiveness of a permaculture system may hinge on the farmer's experience and competence in handling such a multifaceted system. Hence our results suggest, that well planned and managed permaculture systems are able to be as productive as prevalent industrial and especially organic agriculture. Still, on average permaculture seems to be able to reduce the yield gap of organic agriculture while still working according to its guidelines. A global meta-analysis revealed that, mean organic agriculture yields were 25% lower compared to those of conventional agriculture (Seufert et al., 2012). At the same time, permaculture seems to strongly improve environmental conditions of the agroecosystem in terms of soil quality, carbon storage and biodiversity (Reiff et al., 2024).

Table 2: Statistics. Results of t-Tests and linear models on the Land-Equivalent-Ratios (LER) of 11 permaculture sites as compared to total German agriculture and to German organic agriculture fitted in R.

Response variable	Test	Explanatory variable	t/F-value	P-value	df
LER (total)	One sample t-Test against 1	NA	-1.62	0.137	10
LER (total)	Linear model	Age	<0.00	0.995	7
LER (total)	Linear model	Investigated area	0.02	0.904	7
LER (total)	Linear model	Presence of livestock	0.24	0.641	7
LER (organic)	One sample t-Test against 1	NA	1.98	0.087	10
LER (organic)	Linear model	Age	0.03	0.864	7
LER (organic)	Linear model	Investigated area	0.13	0.734	7
LER (organic)	Linear model	Presence of livestock	0.18	0.688	7

A total of 78 crop varieties were found on the permaculture plots to calculate LER values. The permaculture sites produced a total of of 93.6 % vegetables, 5.8% tree crops and 0.5% soft fruit. Common permaculture literature suggests to rely on annual crops until woody crops are established and reaching full yield (Shepard, 2013; Perkins, 2016). The high proportion of vegetable yield found on all permaculture sites in this study aligns with their recent establishment (Tab 1, Tab 3). The viability of permaculture sites relying mainly on vegetables could be evidenced in a case study in France. Here, on a permaculture site measuring 1000 m^2 one person produced an income ranging from 900 to 1600 € per month, with a mean workload of 43 hours per week (Morel et al., 2015). In addition, a study in the USA found permaculture farms to fit well within the emerging framework of diversified farming systems, with a high diversity of production and income, including non-production enterprises, to develop and maintain diverse agroecosystems (Ferguson and Lovell, 2017). In Malawi, farmers experienced economic and nutritional benefits from utilizing permaculture through increased, more diverse and more stable yields (Conrad, 2014). This first study on permaculture yields in Central Europe demonstrates that permaculture also has the potential to compete with industrial methods in temperate climates.

Table 3: Crop yield of permaculture sites. Land-Equivalent-Ratio of eleven permaculture sites in Germany and neighbouring countries as compared to total (LER total) and organic (LER organic) German agriculture. Yield includes crop yield of vegetables, tree crops and soft fruit. The proportions of vegetable groups, soft fruit, tree fruit and tree nut in the total yield of the permaculture site are given as percentage values.

site	LER total	LER organic	yield [t/ha]	root/tuber veg. [%]	fruit veg. [%]	cabbage veg. [%]	leaf/stalk veg. [%]	legume [%]	other veg. [%]	soft fruit [%]	tree fruit [%]	tree nut [%]
1	1,30	2,67	20	4	68	1	13	0,5	0,0	13,4	0,0	0,0
2	1,02	1,70	17	30	18	21	26	4,8	0,0	0,0	0,0	0,0
3	0,27	0,48	32	29	33	14	7	2,5	0,0	1,4	11,8	0,3
4	0,55	0,92	7	37	37	6	18	0,5	0,0	2,1	0,0	0,0
5	0,33	0,59	31	21	24	17	20	1,4	0,0	0,1	17,0	0,0
6	1,10	2,06	12	17	39	10	29	4,2	0,1	0,0	0,0	0,0
7	0,91	1,44	7	27	25	3	41	3,9	0,0	0,0	0,0	0,0
8	0,44	0,81	32	37	21	27	15	0,6	0,0	0,0	0,0	0,0
9	1,51	2,67	45	27	41	13	14	4,0	0,0	0,2	0,0	0,0
10	0,57	0,96	11	19	9	17	31	6,0	0,1	6,4	11,4	0,0
11	0,81	1,59	26	13	33	7	44	0,3	2,1	0,0	0,0	0,0

Conclusion

For the first time, our findings suggest that well-planned and managed permaculture systems can obtain productivity levels comparable to industrial agriculture while adhering to guidelines of organic agriculture. This highlights the potential of permaculture to bridge the productivity gap between organic and conventional agriculture, while regenerating agroecosystems.. Further promotion and adoption of permaculture principles could enhance sustainable food production and reduce reliance on industrial farming methods.

The high variance of LER values among individual permaculture sites in this study indicates the need for more research to understand the factors influencing productivity in permaculture systems. Future studies should investigate larger samples of permaculture systems from different continents and climates, as well as the level of complexity, management intensity, and farmer experience to determine their impact on permaculture yields. Additionally, exploring long-term effects of older permaculture systems, including staple crop (e.g. grains) and livestock yield, and comparing them to conventional agricultural practices would provide valuable and much needed insights.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

Funding acquisition, methodology development and original draft preparation were done by Julius Reiff. Data acquisition and analysis was done by Julius Reiff and Nicole Antes. Conceptualization was done by Hermann F Jungkunst, Martin H Entling and Julius Reiff. Review and editing was done by all Co-Autors.

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Chapter 5

Synthesis and Outlook

Julius Reiff

Contribution of permaculture

In Chapter 2 we showed, that despite its separation from science, there is a foundation of scientific evidence supporting the twelve permaculture principles introduced by David Holmgren. We also found a strong overlap with agroecological principles, especially for the ones related to the structure of agroecosystems. In addition, permaculture includes principles to guide the design, implementation and maintenance of resilient agroecological systems making it an important potential link between (scientific) theory and practice. To summarize, the utilization of the permaculture principles should allow to design and operate productive and resilient agroecosystems, that take advantage of a high biodiversity, regenerate soils and minimize dependencies on industrial inputs.

These holistic effects could, to a large extend, be confirmed by investigations of commercial permaculture farms described in Chapters 3 and 4. We found (partly very strong) positive effects of permaculture on soil organic carbon, soil quality and biodiversity with average crop productivity comparable to predominant industrial agriculture (Figure 1).

Hereby, permaculture aligns well with current important initiatives. The "4 per 1000" initiative, launched during the United Nations Climate Change Conference in Paris 2015, aims to increase the organic carbon content of soils by 0.4% (or 4‰) per year (Minasny et al. 2017). We estimated average soil carbon sequestration on permaculture plots exceeding this threshold (Chapter 3). This annual increase in global soil carbon stocks would significantly offset the annual increase in atmospheric carbon dioxide, which is essential to prevent serious consequences of climate change such as the mass famines outlined in Chapter 1.

The “4 per 1000” initiative is a partner of the United Nations Decade on Ecosystem Restoration. This program aims to halt and reverse the ongoing degradation of ecosystems worldwide to provide crucial ecosystem services and support human needs for sustainable production and livelihoods (UNEP 2021). For farmland an establishment of regenerative agriculture is suggested to restore soil carbon, soil health and on-farm biodiversity (UNEP 2021). In Chapter 3 we highlighted, that permaculture is able to design, establish and manage such a regenerative agriculture being an effective tool to implement the restoration of farmland ecosystems.

This restoration and sustainable management of agroecosystems is imperative to achieve the United Nations Sustainable Development Goals (SDG’s) (Dubey et al. 2021). The results of Chapters 3 and 4 show, that permaculture can significantly contribute to these goals in various ways. Permaculture produced yields comparable to industrial agriculture. In addition, these yields exhibited a high dietary diversity while its production was less dependent on industrial inputs e.g. through adoption of organic agriculture (no synthetic pesticides and fertilizer), low mechanization and exploitation of promoted ecosystem services. Hereby permaculture could contribute to promote self-sufficiency of farmers (SDG 1, No Poverty), increase food security (SDG 2, Zero Hunger) and ensure access to a diverse diet, while reducing the use of harmful agrochemicals (SDG 3, Good Health and Well-being). As outlined in the previous two paragraphs, permaculture also led to a substantial increase in soil organic carbon (SDG 13, Climate Action) and a restoration of farmland ecosystems (SDG 15, Life on Land). However, consistently adhering to the permaculture principles and ethics (Chapter 2), not just in agriculture but also in economy and society, would possibly contribute even stronger and to additional Sustainable Development Goals.

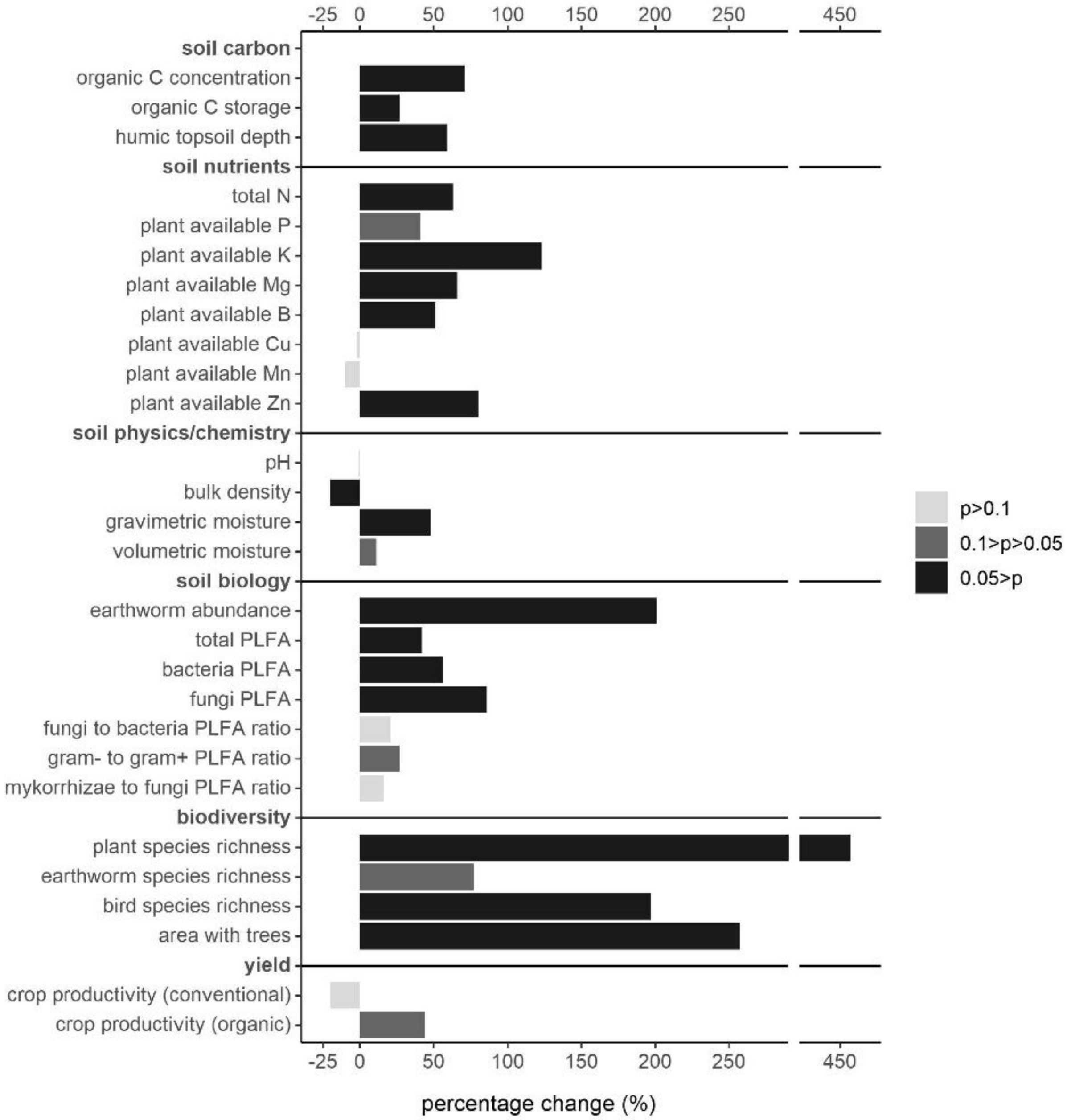

Figure 1: Percentage change of various indicators of soil carbon, soil quality, biodiversity and yield for permaculture. Indicators of soil carbon, soil quality and biodiversity were assessed on nine permaculture plots compared to paired control fields of locally predominant agriculture. Crop productivity was assessed using the Land Equivalent Ratio of eleven permaculture plots as compared to total and organic German agriculture. Four permaculture plots were part of both assessments. Levels of significance are displayed as different bar colour in shades of grey.

A need for research

While both Chapters 3 and 4 underscore the promising potential of permaculture in enhancing environmental sustainability while maintaining productivity, they also highlight a significant degree of variability in their findings. This variability, soil properties, biodiversity indicators and Land Equivalent Ratios (LER), suggests that permaculture's effectiveness is likely influenced by a complex interplay of various factors such as adopted practices and land use types, system complexity, management intensity and farmer experience. Such heterogeneity in outcomes necessitates further comprehensive research to isolate and understand the variables contributing to these divergent results. Future investigations should aim to include larger and more diverse samples of permaculture plots across different climatic zones and agricultural contexts. This would not only provide a more robust dataset but also offer insights into the scalability and adaptability of permaculture practices. In addition, increased (micro-)nutrient and organic carbon levels of permaculture soils found in Chapter 3 (Hornick 1992; Wood, Tirfessa, and Baudron 2018) together with traditional cultivars (Dwivedi, Goldman, and Ortiz 2019) and a pesticide-free cultivation (Hornick 1992; Ali et al. 2021), might produce healthier and more nutritious foods. Therefore a nutritional investigation of permaculture produce is important to reveal possible health benefits.

This traditional reductionistic approaches, although valuable for isolating specific variables, is not able to capture the intricate dynamics and synergies inherent in complex systems such as permaculture (Douthwaite and Hoffecker 2017). Therefore, in addition to these methods, future research also needs to employ frameworks grounded in complexity theory and systems thinking (Douthwaite and Hoffecker 2017). These approaches can provide a more nuanced understanding of the emergent properties, feedback loops, synergies and multi-scale interactions that characterize permaculture (Morel, Léger, and Ferguson 2018). This is necessary to reveal the essential knowledge on the structure of these systems, instead of only increasing the knowledge about the state and condition. By integrating both reductionistic and systems-based methodologies, researchers can develop a more comprehensive and actionable body of knowledge. This multi-faceted approach is crucial for optimizing resilient, productive and self-sustaining agricultural systems to facilitate the transition toward more sustainable agricultural paradigms.

But time to act

In the face of urgent environmental crises such as escalating climate change, severe soil degradation, and rapid biodiversity loss, the imperative for immediate action has never been greater. In 2017 more than 15 000 scientists from across the globe signed a warning to humanity that we are severely overexploiting the capacity of our plant causing a potentially catastrophic climate change, a mass extinction event and threatening human life on earth (Ripple et al. 2017). This article and the initiatives mentioned above already provide an extensive list of diverse and efficient tools for a transition to more sustainability, that do not depend on additional research.

“But tools are no use if you don’t use them. We need action, ambition and political will.” *António Guterres, Secretary-General of the United Nations (United Nations 2019)*

While further scientific evaluation of permaculture systems and sustainable agricultural practices is undoubtedly valuable, it should not serve as a prerequisite for taking decisive steps towards a transition of agriculture. In this context, research can run in parallel, serving to refine and optimize practices, but it should not delay or divert resources away from the urgent actions that are needed now.

From this perspective, the role of transdisciplinary research becomes pivotal. It synthesizes insights from various disciplines - ranging from ecology and economics to social sciences - to provide a nuanced, systems-level understanding that adapts and informs ongoing initiatives by participatory interactions (Francis et al. 2008). This inclusive and holistic approach not only accelerates the translation of research into practice but is also able to ensure that the solutions are socially, economically, and environmentally sustainable (Brandt et al. 2013). In this way, transdisciplinary research acts as a service that enhances the efficacy of immediate actions, rather than a preliminary step that delays them.

Pathways and challenges to large scale implementation

To achieve large-scale implementation of permaculture, a multi-dimensional approach is essential. This course of action has to include related concepts like agroecology, regenerative agriculture and diversified farming systems.

Firstly, financial incentives must be restructured to favour sustainable farming methods over conventional ones (Díaz-Siefer et al. 2022). This could be achieved by increasing taxes on energy, irrigation water, pesticides, and mineral fertilizers, making them less economically viable and systems, that are less dependent on external inputs, more appealing. The revenue generated from these taxes as well as previous subsidies for industrial agriculture could be redirected into subsidies or grants that support sustainable farming approaches such as agroforestry, crop-livestock integration, holistic grazing management, marked gardening and permanent soil cover.

Secondly, the educational system for farmers needs a significant overhaul. As an example, the education regulations for farmers in Germany were last revised in 1995, 28 years ago (Federal Ministry of Justice 2023). Curricula necessarily need to include not just permaculture but also agroecology, regenerative agriculture and diversified farming systems as well as related practices. The aim is to equip farmers with the knowledge and skills they need to transition from conventional industrial to regenerative farming.

Thirdly, the initiation of flagship projects can serve as live case studies to demonstrate the efficacy of these sustainable farming methods. These projects could be funded by the government or private investors and serve as replicable models for specific geographical and climatic conditions. The success of these projects would not only validate the approach but also inspire other farmers to be part of a favourable transition.

While certification and labelling might seem like a logical step, they could actually be counterproductive in the case of permaculture. Such formal systems could create hurdles for farmers and undermine the individual and context-based approach that is central to permaculture. Instead, support should be given to regenerative practices that are utilized by sustainable farming approaches. This could be in the form of grants, subsidies (see above), and especially technical support to help farmers to design a resilient farming system and adopt necessary practices. In addition, a public awareness campaign could be more effective than labelling in educating consumers on environmental and health benefits of produce grown through permaculture and related methods, thereby driving market demand.

Implementing permaculture on a large scale in agriculture naturally also faces several challenges. Initially, permaculture systems often produce lower yields compared to conventional methods, making it tough to compete in the market. The approach is also labor-intensive, due to the diverse range of crops and complex management practices required (Ferguson and Lovell 2017). Additionally, scaling permaculture principles to large, uniform land areas presents significant difficulties, as the method's success hinges on efficiency thanks to small-scale systems, high diversity and localized adaptation, which are harder to achieve on a larger scale.

These challenges can be overcome through the careful application of permaculture principles, as evidenced by the example of the New Forest Farm, a highly productive perennial agricultural forest of 43 ha in Viola, Wisconsin, USA. For reference, 68 % of farms in Germany are smaller than 50ha (BMEL 2022). In the case of the New Forest Farm, a succession process was employed, whereby more vegetables were cultivated initially until the trees reached a sufficient yield, in order to emulate the natural growth patterns observed in natural ecosystems (Shepard 2013). Moreover, there is no reason why technology should not be borrowed in permaculture. For instance, full harvesters are used on that farm to harvest hazelnut bushes. Additionally, a modular approach to scalability is possible, whereby a large farm is divided into several smaller sub-farms in order to implement the principles of permaculture (Holmgren 2002). This may prove to be a pivotal supplementary strategy for the implementation of permaculture on a larger scale, with the objective of achieving a substantial environmental impact. This is particularly relevant given that, in the case of Germany, 41% of agricultural land is currently managed by farms exceeding 200 ha in size (BMEL 2022).

In conclusion, the priority must be to act swiftly and effectively to mitigate the pressing environmental issues we face, using research as a tool for continuous improvement rather than a hurdle to be cleared before taking action.

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Appendix

Status and author contributions of publications included in the thesis

Declaration of Generative AI technologies in the writing process

Curriculum vitae

Declaration

Status and author contributions of publications included in the thesis

Chapter 2

Krebs, J., & Bach, S. (2018). Permaculture—Scientific evidence of principles for the agroecological design of farming systems. *Sustainability*, *10*(9), 3218. https://doi.org/10.3390/su10093218

Status: published

J.K. conceptualized the review and conducted the literature search for the permaculture principles; S.L. drafted the introduction and the agroecology section. **Both authors** equally contributed to the writing.

Chapter 3

Reiff, J., Jungkunst H. F., Mauser K. M., Kampel S., Regending S., Rösch V., Zaller J. G. & Entling M. H. (2024). Permaculture enhances carbon stocks, soil quality and biodiversity in Central Europe. Communications Earth & Environment, 5(1), 305. https://doi.org/10.1038/s43247-024-01405-8

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Funding acquisition, sampling, visualization and original draft preparation were done by **Julius Reiff.** Conceptualization and methodology development were done by **Julius Reiff,** Martin H. Entling and Hermann F. Jungkunst. Analysis of phospholipid-fatty-acids was done by Ken M. Mauser. Identification of earthworm species was done by Sophie Kampel and Johann G. Zaller. Identification of bird species by means of recorded songs and calls was done by Sophie Regending and Verena Rösch. **All authors** contributed to review and editing.

Chapter 4

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Status: submitted

Funding acquisition, methodology development and original draft preparation were done by **Julius Reiff**. Data acquisition and analysis was done by **Julius Reiff** and Nicole Antes. Conceptualization was done by Hermann F Jungkunst, Martin H Entling and **Julius Reiff**. Review and editing was done by **all Co-Autors**.

Declaration of Generative AI technologies in the writing process

During the preparation of the abstract, the ‘general introduction’ and the ‘synthesis and outlook’ chapters the author partially used ChatGPT 4 and DeepL in order to improve English language wording. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the text.

Curriculum vitae

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10/2014 – 04/2017	**M.Sc. Environmental Sciences** University of Koblenz-Landau, Germany
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Publications

Reiff, J., Jungkunst H. F., Mauser K. M., Kampel S., Regending S., Rösch V., Zaller J. G. & Entling M. H. (2024). Permaculture enhances carbon stocks, soil quality and biodiversity in Central Europe. Communications Earth & Environment, 5(1), 305.

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Declaration

I hereby declare that I independently conducted the work presented in this thesis entitled *Sustainability of Permaculture Farming*. All used assistances are mentioned and involved contributors are either co-authors of or are acknowledged in the respective publication. This thesis has never been submitted elsewhere for an examination, as a thesis or for evaluation in a similar context to any department of this university or any scientific institution. I am aware that a violation of the aforementioned conditions can have legal consequences.

Julius Reiff, Landau, 08.08.2024