

Review

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

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Received: 30 June 2018; Accepted: 6 September 2018; Published: 8 September 2018



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 farming 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-ordinator, 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 NO_x 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]. Mycorrhizas 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 world'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 mycorrhizza 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.

Author Contributions: 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.

Funding: The TU Braunschweig has funded the costs to publish in open access.

Acknowledgments: We would like to thank our supervisors Martin Entling and Boris Schröder-Esselbach for their support and their contributions to editing this review. Also, we would like to thank our three reviewers for their valuable suggestions which have enriched this article and Paul Mason for language support.

Conflicts of Interest: The authors declare no conflict of interest.

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