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

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1 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 Germany and surrounding countries. 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. Provided that future studies will support our findings, permaculture could combine soil, biodiversity and climate protection with agricultural productivity. Most importantly, the variables that determine the difference in crop productivity amoung permaculture sites need to be identified and evaluated.

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

2 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 (Millennium Ecosystem Assessment 2005; Foley et al. 2005; Campbell et al. 2017). In response to these challenges, alternative farming approaches, that prioritize ecological sustainability and regenerative practices are gaining increased attention, such as agroecology (Barrios et al. 2020), regenerative agriculture (Schreefel et al. 2020) or diversified farming systems (Kremen et al. 2012). A promising framework for the design and management of those food production systems is permaculture (Mollison 1992; Ferguson and Lovell 2014; Krebs and Bach 2018).

Permaculture is an agroecological design system that draws inspiration from natural ecosystems and traditional and indigenous farming practices (Mollison 1992). 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 (Morel et al. 2019). By mimicking the patterns and relationships found in natural ecosystems, permaculture seeks to optimize resaource use, promote biodiversity and enhance ecosystem health (Ferguson and Lovell 2014). 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 (Krebs and Bach 2018). Amongst others, permaculture principles emphasize practices like 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 (Reiff et al. 2024).

Implementing these principles, permaculture sites showed strong improvements in soil quality, soil carbon storage and biodiversity compared to predominant agriculture in Central Europe (Reiff et al. 2024). 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 (Holmgren 2002).

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 (Morel et al. 2019). The few existing studies have focused only on economic performance (Morel et al. 2015), income diversity (Ferguson and Lovell 2017) or qualitative interviews of farmers (Conrad 2014). 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 (Martin-Guay et al. 2018). 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 (Deb 2021; Deb et al. 2022). 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 (Böhm et al. 2020), or they were estimated from the intercropping experiment itself (Seserman et al. 2018). The approach of using maximum or average sole crop yields was also described by (Mead and Willey 1980). 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.

3 Materials and methods

3.1 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 and grazing areas 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 (Reiff et al. 2024). These sites share identical identifiers in both studies.

3.2 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 (Federal Statistical Office 2023a), potatoes (Federal Statistical Office 2023b), tree fruit (Federal Statistical Office 2023c), and other soft fruit (Federal Statistical Office 2023d). 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 (Blickensdörfer et al. 2022). 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 (Cerović et al. 2010) and hazelnut (Erdogan 2018) 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).

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

3.3 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 (Mead and Willey 1980; Risch and Hansen 1982; Bomford 2009; Reynafarje et al. 2016; Paut 2018). 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. Example calculation for yield data of permaculture site X from 2019 in comparison with total German agriculture and of just two crop varieties:

$$LER_{tot,siteX} = \frac{Y_{siteX}(potatoes)}{Y_{tot,2019}(potatoes)} + \frac{Y_{siteX}(bush\,bean)}{Y_{tot,2019}(bush\,bean)} = \frac{25\,t/ha}{39\,t/ha} + \frac{5\,t/ha}{10\,t/ha} = 0.64 + 0.5 = 1.14$$

3.4 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 (Fox et al. 2023) 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.

4 Results

A total of 79 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.

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 a non-significant 20% lower permaculture productivity. Consequently these results suggest a by trend 44% higher permaculture productivity compared to organic German agriculture.

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).

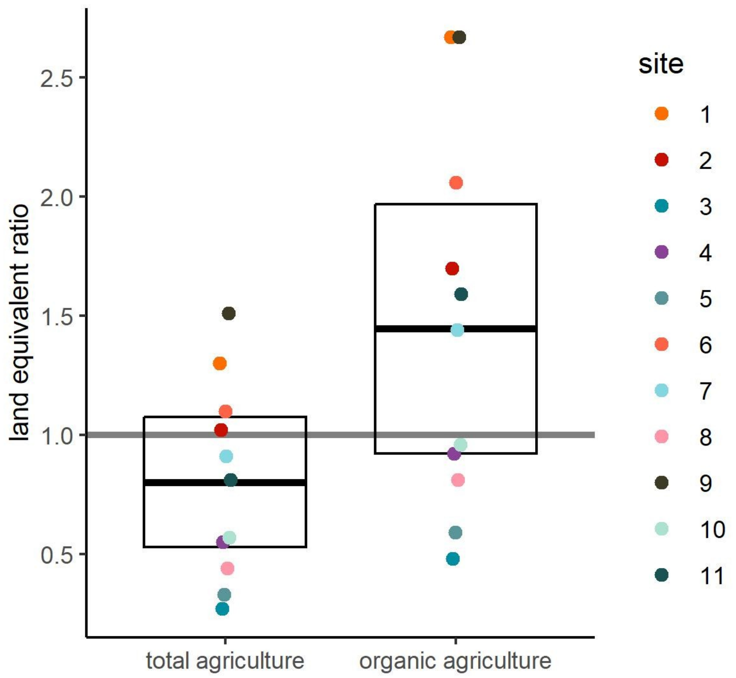

Figure 1: Land equivalent ratios (LER) of permaculture. LER's of eleven permaculture sites as compared to total ($p=0.137$, $t=-1.62$, $df=10$) and organic ($p=0.087$, $t=1.98$, $df=10$) German agriculture. Bars with error bars indicate mean and 95% confidence interval, coloured dots indicate individual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

5 Discussion

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. The by trend higher productivity compared to German organic agriculture even suggests a potential of permaculture to bridge the productivity gap between organic and conventional 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.

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.

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	0.8[illegible]4	7
LER (organic)	Linear model	Investigated area	0.13	0.734	7
LER (organic)	Linear model	Presence of livestock	0.18	0.688	7

LER values were not significantly dependent on any of the tested predictor variables. 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 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

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.

6 Conclusion

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 limited scope of this study with eleven sites and yield data from only one year needs further and larger studies to confirm our results. In addition, the high variance of LER values among individual permaculture sites indicates the need for more research focused on understanding 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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8 Conflict of Interest

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

9 Availability of data and material

The datasets generated during and/or analyzed during the current study will be made openly available.

10 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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