Edible production potential of food forests in the temperate zone

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Acknowledgements

About a year ago, I knew very little about the phenomenon of food forests, but when it caught my attention and I started reading about it, I saw them everywhere. Thanks to the algorithms, of course. Now, about a year later, I have seen multiple food forests myself, I have met the most passionate food forest owners, and I am glad to say that I have finished my master's thesis about food forests.

There are a lot of people who have helped me in the most diverse ways throughout this journey, but a few need special attention. First of all, thank you, Peter van Bodegom, for the supervision and directing me in the right direction at moments I wasn't sure what to do. Thanks to Laura Scherer, also for her supervision and the very sharp and on-point feedback, sometimes with a subtle touch of sarcasm, which I really liked. Bram Wendel from the NMVB for making it possible to conduct a study with such a practical body. And last but surely not least, Lieke Moereels, for the formal and informal help throughout this project, for the great four weeks of fieldwork that we did together, and for being the always kind and enthusiastic person you are. And of course, I have to thank all the food foresters that opened their forests to us and always warmly welcomed us; without you, this study could never have taken place.

Summary

Food forests have recently received an increasing amount of attention since they are seen as a possible addition to the Dutch nitrogen-sensitive agricultural sector. Food forests are claimed to positively affect local ecosystem services while producing food for human consumption. Most of the effects and the edible production, however, lack scientific and quantified substantiation. This study aims at quantifying the edible production of food forests in the temperate climate zone, compares it to conventional agricultural systems, and analyses factors that may influence the edible productivity. By monitoring 22 100 m^2 plots in eight food forests in the Netherlands and Belgium, it was found that the average food forest of this set of food forests produces 1038 kg edible biomass, 948,344 kcal, 12.39 kg proteins, 104.59 kg carbohydrates, and 22.13 kg fats per hectare. Except for carbohydrates in conventional hazelnut production and fats in conventional red and black currant production, the food forests' edible production, consisting of a diverse set of fruits, turned out to contain significantly lower amounts of energy, proteins, carbohydrates, and fats than conventional apple, pear, red currant, black currant, hazelnut, and dairy production in the Netherlands. Furthermore, no significant relationships were found between age, species richness, or canopy cover and the edible production of the food forests. Management and design, however, are considered factors that likely affect the edible production and need to be analysed in future work. Although food forests have not turned out to be competitive with conventional production systems in terms of edible production, they have many more beneficial characteristics than food production alone. More than conventional agricultural systems, food forests are expected to contribute to biodiversity, carbon capture, natural habitat creation, and soil formation and offer possibilities for social aspects like local community building and education. They are therefore still considered a valuable addition to the Dutch agricultural sector, although less productive and with fewer financial incentives, but more in line with nature-inclusive and circular forms of agriculture and with more focus on social opportunities.

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Glossary

Agriculture	The practice of cultivating the soil for the production of crops or raising animals with the main goal of providing food for humans.
Agroforestry	An agricultural system where pasture or crop producing practices are integrated with trees and shrubs.
Conventional (production) systems	Modern intensive agricultural production systems.
Ecosystem services	Benefits that ecosystems provide to people and nature. Examples: pollination, clean air generation, waste decomposition, food production, etc.
Food forest	A diverse agroforestry system of food-producing species. Existing out of at least three layers of which one must be the canopy layer.
Production	The amount of output from a certain system, usually in mass or energy (e.g. kg; kcal).
Productivity	The ratio of output to inputs. In agriculture, it generally refers to how efficiently resources (e.g., energy) are used to produce outputs (e.g., fruits).
Species level	Research level in which a specific species is examined and where its functioning is compared within different systems.
Species richness	The number of different species in a specified area.
System level	Research level in which a whole agricultural system (e.g., food forests) is examined and compared with other systems.
Yield	The amount of harvested products in mass or absolute numbers per area (e.g. kg ha^{-1}).

1. Introduction

1.1. Agricultural developments in the Netherlands

Food production through agricultural activities has enormously increased in the past half-century. In order to contribute to the growing food market, agricultural production has evolved from a system where the farmer worked together with nature in an ecological way into a highly intensified industry (Verburg et al., 2022). Although the food production of the Dutch system has increased; potato production has grown more than 50% and dairy and pork production have doubled since the 1970s (CBS, 2023), agricultural activities have also increased greenhouse gas (GHG) emissions and negatively impacted ecosystem services like biodiversity and pollination (Centeno-Alvarado et al., 2023; Hodge et al., 2015). In 2021, the Dutch agricultural sector was responsible for 16% of the Dutch GHG emissions (CBS, 2022) and is hence the fourth largest GHG emitting sector in the country. Moreover, the nitrogen emissions from livestock account for nearly 50% of the total nitrogen pollution in the Netherlands (Stokstad, 2019), negatively affecting nature reserves and putting the country in the so-called nitrogen crisis.

The urgency of decreasing the emissions of the agricultural sector is captured in multiple international agreements like the European Green Deal (European Commission, 2019), the Farm to Fork Strategy (European Commission, 2020), the EU Biodiversity Strategy 2030 (European Commission, 2021), and the Common Agricultural Policy (European Commission, 2022). All these policies strive to lessen GHG and nitrogen emissions, fertiliser and pesticide use, increase carbon capture, and promote organic and nature-inclusive farming; in other words, they strive for an agricultural system that is in line with an ecologically responsible industry.

The nitrogen crisis and the European policies are pushing the Netherlands into a transition of the agricultural sector. As a result of this transition, the government will force the most polluting farmers to stop, replace, or change their activities. By forcing farmers to stop their daily practices, lots of arable land may become available. It is still unknown what will happen with these lands (Linders, 2022), but from a food security perspective, it is preferred to keep the land in use for food production, but in an alternative way. However, the effects of alternative, less commonly used forms of agriculture on ecosystem services are often unknown and understudied (Giller et al., 2021; Wartman et al., 2018).

1.2. Alternative forms of agriculture

Regenerative agriculture consists of alternative forms of agriculture that focus on circularity. Schreefel et al. (2020) defined it as '*an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting ecosystem services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production.'* Next to emitting fewer emissions, regenerative agriculture also strengthens the agroecosystem itself by, e.g., improving heat resistance through better soil quality and making the system more resilient to climate change (Brown et al., 2022; Buiter & de Waard, 2017; Lovell et al., 2018). Multiple forms of agricultural production systems meet this definition. It depends, however, on geographical conditions if and which form of regenerative agriculture is best suitable (Schreefel et al., 2022).

Among the different forms of regenerative agriculture, agroforestry is the one with the greatest potential to mitigate climate change (Giller et al., 2021). Agroforestry is a rather old practice, but is lately gaining an increasing amount of attention (Nerlich et al., 2013; Wartman et al., 2018). Multiple forms of agroforestry have a long history in Europe but have been degraded due to the intensification of agriculture. Since attention is currently shifting from intensification to extensification and increasing biodiversity, agroforestry systems are regaining popularity. By utilising natural nutrient cycles, a decreased amount of additional nutrients through fertilisers has to be added, and by diversifying plant and tree species, biodiversity within these systems will increase (Centeno-Alvarado et al., 2023). Examples of agroforestry systems are alley cropping or silvoarable systems, where traditional crops are grown in between lanes of trees; silvopastoral systems, where grass is grown underneath trees to feed livestock; and forest farming, where trees are dominant and shade-tolerant crops are grown underneath (Nerlich et al., 2013; Wartman et al., 2018).

1.3. Food forests

1.3.1. Definition of food forests

An additional form of agroforestry is a food forest. Food forests are agricultural systems where perennial, food-producing species are dominant, supported by non-productive species functioning as, e.g., nitrogen fixers. They generally contain multiple, but at least three, layers: the canopy layer, containing high trees; the mid-layer, containing medium-high trees; the low-layer, containing shrubs; the herbaceous layer, containing herbs; and the ground layer, containing root crops (de Groot & Veen, 2017). Food forests mimic natural forests and are aimed at being low-maintenance, minimising the inputs of fertiliser, pesticides, and irrigation (Lehmann et al., 2019). Their main general objective is food production, while secondary objectives are improving ecosystem services like carbon capture, soil regeneration, and pollination (Albrecht & Wiek, 2021a; Ickowitz et al., 2022). In addition to the benefits of ecosystem services, they often play a social role by building local communities and providing education and recreation (Albrecht & Wiek, 2021a).

Among all forms of agroforestry, food forests are expected to be most beneficial to local biodiversity and ecosystem services like carbon capture and habitat creation, but the yield potential of the perennial, multi-layered system is unknown (Wartman et al., 2018). Because food forests have high expected potentials but also vast unknowns, this study will focus on the quantification of the effects food forests have on their ecosystem services.

1.3.2. Viability of food forests

Frequently, food foresters earn the most of their income through social activities or social subsidies, while edible production is to a lesser extent a source of income and often functions as a side business (Albrecht & Wiek, 2021b). Therefore, most food forests lack economic viability and a profitable, sustainable business model. It is often hard to create a stable market for their products since their yields fluctuate over the years and they cannot always guarantee a certain offer. Specific farming education on food forests and entrepreneurial training could remedy this deficit and turn the social and environmental services of food forests into economic viability (Albrecht & Wiek, 2021a). Increased scientific knowledge about the ecosystem services of food forests, their potential, and opportunities can be incorporated into these trainings.

Wartman et al. (2018) mention an important issue regarding the scale-up from small, social forests to bigger commercial food forests. Where ecosystem services like space for wildlife thrive better in smaller forests with a high diversity of species, manageability gets increasingly difficult. A balance has to be found between species diversity and manageability in order to improve ecosystem services as much as possible while establishing an economically beneficial food forest. Nowadays, an increasing number of new food forests is being designed, especially for more efficient food production with less focus on social side activities. Although many ecosystem services thrive well in these new food forests, due to economic interests, the edible production is being prioritised over others.

1.4. Edible production

Many scientific studies have demonstrated a positive relationship between species richness and productivity (Erskine et al., 2006; Isbell et al., 2009; Tilman et al., 2012). In that context, it has been hypothesised that food forests (consisting of multiple species) should be able to produce more than monocultures. However, most of these studies have measured productivity in terms of biomass. Studies that have measured productivity in terms of edible production are less available but upcoming (Renard & Tilman, 2021). Even fewer have studied the edible production within food forest systems, while many have claimed that food forests play an important role in food security (Cieremans, 2020; Wageningen University & Research, n.d.). In total, three studies about the edible production of food forests have been conducted (Boulestreau & van Eck, n.d.; Nytofte & Henriksen, 2019; van Eeden, 2020), of which only one used real harvest data.

Nytofte & Henriksen (2019) measured the edible production potential of a 0.08-hectare food forest, established in 1991 and in practice for over 26 years and found that it could feed 3 to 9 persons per hectare. Van Eeden (2020) modelled the food production of a single food forest in the Netherlands and calculated the potential production in 2049. The food forest he modelled has the potential to feed 11 (kcal) to 23 (fibres) persons per hectare. Lastly, Boulestreau & van Eck (n.d.) modelled a hypothetical food forest that could potentially feed 7 (proteins) to 14 (fats) persons per hectare. However, practical factors like disappointing weather conditions and pests might change the outcomes of the modelled studies, demanding more observatory studies based on real harvest data. Table 1 shows the edible production in terms of the nutritional outputs of the above-mentioned studies.

Table 1. Biomass, energy, and nutritional outputs of previous studies. Data is derived through real data collection (Nytofte & Henriksen) and modelling (Van Eeden and Boulestreau & Van Eck).

	Biomass (kg/ha)	Energy (kcal/ha)	Carbohydrates (kg/ha)	Protein (kg/ha)	Fat (kg/ha)
Nytofte & Henriksen	5.750	3.766.334	773.790	46.186	90.051
Van Eeden	-	9.324.554	910.395	284.214	476.957
Boulestreau & Van Eck	5.681	4.937.023	601.095	85.875	250.347

While an increasing amount of arable land may become available due to the nitrogen crisis, it is still unknown to farmers if they can create viable business cases by starting a food forest. Quantification of the edible production of the current status quo of food forests in the Netherlands will be the basis for these business cases. Moreover, quantified production data might offer opportunities for research regarding the productivity of food forests. Therefore, the edible production of food forests will be the examined ecosystem service in this study.

1.5. Knowledge gap and research questions

Lovell et al. (2018) strongly recommended that more research into the ecosystem services agroforestry provides has to be done with the main goal of '*optimization of the system for greater productivity, without substantial loss of other ecosystem services.'* Food forests are expected to increase soil quality and life, biodiversity, and food productivity (Ickowitz et al., 2022), but practical, data-driven evidence is frequently lacking (Centeno-Alvarado et al., 2023; Lovell et al., 2018; *Monitoringsprogramma Voedselbossen – Green Deal Voedselbossen*, n.d.). Therefore, studies quantifying different ecosystem services of food forests (e.g. edible production) are needed as substantiation for policies, business models, and further research (Albrecht & Wiek, 2021a, 2021b; Nytofte & Henriksen, 2019). In the current situation in the Netherlands, where an increasing amount of arable land may become available on which more regenerative agricultural systems may establish, deeper knowledge of the potentials of these systems is needed to allow broad adoption.

The goal of this study is to show the potential a food forest has as a replacement for grasslands in terms of edible production compared to conventional production systems. Moreover, this study will quantify the status quo of the edible production of food forests in the Netherlands and Belgium, or in a wider context, in temperate climate zones, by using real harvest data. The results inform national or regional policies regarding the potential of food forests as possible repurpose of bought-up agricultural grasslands. For farmers, this comparative study can be the basis upon which future farming plans can be built, while the outcomes of the quantification of the edible production can be used as the basis for future studies regarding the productivity of food forests. The following research question was addressed:

> *What factors influence the edible production of temperate food forests and how does the edible production compare to conventional food production systems?*

In order to gain an overall understanding of the edible production potential of food forests, the literature and collected data will be analysed to answer the following sub-questions.

I. *What is the edible production of woody species in temperate food forests?*

This question will be addressed by the collection and quantification of edible production data from a monitored set of food forests in the Netherlands and Belgium. The collected harvest data will be converted to the nutritional outputs expressed in energy, proteins, carbohydrates, and fats per hectare. In order to detect differences in the nutritional values per kilogramme harvest, the nutrient densities of the harvested products from the forests will be compared.

II. *How does the edible production of food forests compare to that of conventional agricultural systems?*

Exploring how the edible production of food forests relates to the production of conventional agricultural systems is the first step in determining the potential of food forests in the Dutch agricultural sector. This relationship is explored at two levels: the system level and the species level. The system level focuses on how the edible production of food forests in general differs from the edible production of conventional production systems. The species level focuses on how the production of a specific species differs between food forests and conventional systems.

Due to the intensity of land use, pesticide use, and fertiliser use, the edible production of conventional systems is hypothesised to be higher than that of food forests.

For individual species, it is more complicated to hypothesise a higher or lower production in food forests. Not using pesticides and synthetic fertilisers would argue for a lower production of food forests. Moreover, the intensified focus on the efficiency of a single species in monocultures advocates for higher amounts of production in conventional systems. However, the higher biodiversity, species richness, and better soil life in food forests all might argue for higher production of individual species in food forests. It is therefore not specifically hypothesized whether the production of single species in food forests is higher or lower than in conventional systems.

III. *How do factors like age, species richness, and canopy cover relate to the edible production of food forests?*

Exploring patterns in factors that could influence the edible production of the food forests might help explain differences between them. Categorisation based on age, species richness, and canopy cover will be an extension to the species level analysis, which is the basis for exploring these patterns.

Multiple trees only start growing fruits after a few years and reach their full production potential when they are mature. Especially for nut trees, it can take up to ten years before they start growing their first nuts, and it might take even longer before their production is maximised. Therefore, it is hypothesised that the age of food forests positively affects edible production.

Theories by Fridley (2001) and Morin et al. (2011) demonstrated that increasing species richness increases the chance that complementary and facilitating species combinations occur, resulting in higher production rates of both species. Therefore, it is hypothesised that species richness positively affects productivity in temperate food forests.

The canopy cover of trees in fruit production systems influences the mass and quality of the grown fruits in multiple ways, of which light and shading are the most important (Nath et al., 2019). Sunlight is a basic requirement for trees and shrubs to grow and produce fruit. It is therefore hypothesised that shrubs have a higher edible production in forests with lower canopy cover. On the other hand, taller trees that are part of the canopy layer are expected not to be affected by the canopy cover since they experience no or less competition for sunlight.

2. Methods

2.1. Participating food forests

For the monitoring of the edible production, plots were set out in 15 food forests spread in the Netherlands and Belgium. The 15 participating food forests were selected in an overarching study of Moereels (personal communications, 2023) based on their age, soil type, and former type of land use. Since it takes time before the effects food forests have on the ecosystem are visible and measurable, the selected food forests had to be at least six years old. For generalisation of the results, the former type of land use had to be about the same; grassland and cropland were therefore selected. It turned out that all food forests that met these criteria had a romantical set-up, i.e., their set-up was rather random and diversification was prioritised over efficient food production. Food forests specifically designed for high production did not meet the age criteria. The complete set of food forests is shown in Table 2. In the overarching study, the effects food forests have on multiple local ecosystem services are analysed. This study does the same but is focused on the edible production.

Table 2. Selected food forests and their characteristics.

Name	Age (years)	Soil type	Previous land use	Area (ha)
FF1	8	Sand	Grassland	0,1
FF2	9	Clay	Grassland	0,5
FF3	9	Loamy sand	Cropland	0,1
FF4	7	Clay	Grassland	0,5
FF5	10	Sand	Grassland	1,4
FF6	9	Loamy sand	Grassland	0,2
FF7	30	Sand	Grassland	1,4
FF8	8	Loam	Cropland	0,7
FF9	12	Sandy loam	Cropland	2,1
FF10	14	Loam	Cropland	1,4
FF11	8	Clay	Grassland	0,3
FF12	14	Sandy loam	Grass- and croplan	0,6
FF13	7	Clay	Grassland	0,1
FF14	28	Sand	Cropland	0,5
FF15	10	Sand	Cropland	0,1

2.2. Plot determination

In these 15 food forests, six plots per forest were randomly generated to create a random sample with an unbiased estimator. Each forest was split up into six equally sized parts, after which in each part a coordinate was randomly chosen to make the north-east corner of a 5x5-metre plot. These 5x5-metre plots of 25 m^2 were used in the overarching study to examine ecosystem services other than food production. In order to capture more species in the plots and therefore better represent the species diversity in the food forests, the plots were enlarged to 10x10 metres (100 m^2) for this study.

In order to prevent the enlarged plots from overlapping each other (and due to time limitations), a selection of the plots was used for the monitoring. Depending on the size of the forests, six, four, or two plots were selected for respectively large (> 1 ha), medium (0.5–1 ha), and small (< 0.5 ha) food forests. In the end, after deciding to skip one plot that was located on an access road, 55 plots were set out, resulting in a 0.55-hectare area of food forests to be monitored.

2.3. Field data

2.3.1. Vegetation recordings

For answering sub-question 1 and 3, vegetation recordings of the woody species were made per plot during June 2023. The focus of this study was restricted to woody species since they account for the largest share of the edible production in food forests. Although the herb and vegetable layers do contribute to the edible production as well, due to practical reasons, it was not feasible to include them in the scope of the study.

In the vegetation recordings, the vertical projected area, the tree trunk diameter at breast height (1.3 m) and/or at ground level (0.2 m), and the height of the individual species were measured. These variables were used to determine the species richness and canopy cover used for sub-question 3. Additionally, estimations were made on how much fruit was present on the trees and shrubs, and it was noted when certain species were already harvested.

2.3.2. Harvest data

The data about the edible production was collected between the vegetation recordings in June and November. Food forest owners and managers collected the fruits and nuts in the plots separately from the rest of the forest and weighted them. Only for the fruits that were already ripe when the vegetation recordings were made, we harvested the fruits and collected the data ourselves. To make the data comparable with other food forests and conventional systems, the data was extrapolated from the monitored plots of 0.01 hectare to one hectare; therefore, the edible production per forest is a hypothetical representation and not necessarily the real edible production of the forests.

2.3.3. Adjustments to the collected data

Due to multiple reasons, parts of the collected data could not be used or had to be adjusted to increase the representativeness of the food forests.

Multiple species ripened before the study started. Therefore, in five plots, the edible production was partially harvested before the plots were set out. The main species for which this study was too late were the autumn olive, cherry, gooseberry, blue honeysuckle, and multiple currants. For the red and black currants, however, enough data from other forests was collected to estimate the production potential of the forests where we were too late, based on the averages of the data that we did have. Adjustments based on these averages were only used to increase the representativeness of the forests at the system level. In analyses at species or plot level, these adjustments would lead to distorted datasets and are therefore not applied. Species that we were too late for and for which no comparable data was available could not have been compensated. Luckily, the estimated production potentials of these species were low, so this lack of data will probably not lead to large differences in the outcomes of the analyses.

Often, food forest owners partially harvested the edible species in the plots, leading to incomplete data. The size of the missed fraction in the data, and therefore the size of the collected fraction, is unknown. Based on comments and estimations of the production made during the fieldwork period at the beginning of this study, an estimation of the fraction size of the collected data with respect to the expected data is made at plot level. For 12 plots, this estimation was lower than 75% and they were therefore omitted from the study. A main reason for this relatively high number of dropouts is the outsourcing of the data collection to the forest owners which was, due to the scale of the study, unavoidable.

Lastly, one forest as a whole and one single plot were considered not in line with the definition of a food forest. Forest FF14 is not actively managed nor maintained and a large part of forest FF8 only exists out of non-productive species, in which one of the plots was located. Since the four plots in FF14 and the single plot in FF8 both had no edible production, they were omitted from the study.

2.4. Edible production data of conventional systems

In order to address research question 2, the edible production data obtained from the monitored set of food forests was compared to different types of conventional production systems. The conventional production systems compared in this study are apple (Elstar and Jonagold), pear, red currant, black currant, hazelnut, and dairy.

2.4.1. Conventional systems

For the edible production of fruit growing systems, data from the quantitative information on fruit growing (KWIN) 2009/2010 (Heijerman-Peppelman & Roelofs, 2010) was used. This data source contains data about the acreage, the average yield per hectare, and multiple financial key figures on 11 different types of fruit produced in the Netherlands. Although the data is from 2009/2010 and the financial figures are outdated, the production data is the most accurate data available and is still being used in the Dutch fruit production sector (Jaco van Bruchum, personal communications, September 7, 2023). Per type of fruit, the data source gives multi-year production data on different types of production, e.g., red currants grown in heated plastic or glass greenhouses (10,410 plants/ha), and red currants grown in ground temporary covered with rain covers (6,670 plants/ha). The production types differ among the different types of fruit. The production types that are most related to food forests were used in the comparisons.

The KWIN database, however, shows the highest volumes of production that are possible in the Dutch fruit-growing sector. In reality, as the database mentions itself, production is strongly dependent on multiple factors like weather conditions, harvest losses, and the craftsmanship of the farmer. Therefore, a correction based on harvest data from the previous five years of Elstar, Jonagold, and Conference derived from Statistics Netherlands (CBS, 2023b) is made to the data. The five-year average of these three species turned out to be 25% lower than the KWIN data. Since only for these three species harvest data was available, this correction was used as a benchmark for the entire KWIN database.

The food forests' data was also compared with conventional hazelnut production. Since the scale on which hazelnuts are being produced in the Netherlands is still small, accurate production data is missing. Different sources claim the production to vary between 1500 and 3000 kg/ha, but in general, 2000 kg/ha is used as a guideline for conventional hazelnut production (Selin-Norén et al., 2019; Ton Baltissen, personal communications, October 11, 2023)

Lastly, since great opportunities for food forests lie in grasslands that may become available as a result of the nitrogen crisis, a comparison was made between the edible production of food forests and conventional dairy farms. For this comparison, the per-hectare nutritional outputs of food forests and dairy farms were compared. For dairy farms, milk production is considered the edible production and land use is the combination of grasslands and other croplands used for fodder production (Wageningen University & Research, 2023).

2.4.2. Nutritional outputs

In order to make the heterogeneous edible production data of the food forests and the homogeneous production data of conventional systems comparable, the biomass data was converted into nutritional outputs expressed in energy and the macronutrients of proteins, carbohydrates, and fats per hectare. The key figures that were used in this conversion were mainly obtained through the Dutch Food

Composition Database (NEVO). For products that were not available in the NEVO, other sources were used. For a complete overview of the key figures per product and their sources, see Appendix A.

Although the nutritional values of products vary per type of agriculture, depending on, e.g., fertiliser use and inputs of other minerals (Lester, 2006; Mditshwa et al., 2017), the same key figures were used for both conventional and food forest products. Due to the immense variability in characteristics among food forests, it is impossible to state that the products from food forests are more or less nutritious than conventionally grown products. Therefore, no differences were applied to differentiate between them.

2.5. Analysis

2.5.1. The edible production of food forests

The collection of the edible production data of the 15 forests and the conversion to nutritional outputs are the basis for the answer to the question of what the edible production of food forests is. The average nutritional outputs of the monitored plots were calculated to represent the food forests of this study and can be used to visually compare the set of monitored food forests to conventional production systems and previous studies.

Since food forests with lower biomass production are expected to have lower production in terms of nutritional outputs as well, the nutrient densities of the food forests were calculated. The nutrient density shows the nutritional outputs (energy, proteins, carbohydrates, and fats) per kilogramme of harvest.

2.5.2. Food forests in relation to conventional production systems

In order to address the second sub-question and to gain insights into how the production from food forests relates to the production of conventional systems, the edible production data was compared at two levels: the system level and the species level.

2.5.2.1. System level

In the system-level analysis, the edible production of the forests is compared to multiple conventional production systems. The yields of all species in the individual food forests were summed and expressed as nutritional outputs per food forest. One-sample one-tailed t-tests were used to analyse the differences between the nutritional outputs of the monitored set of food forests and the average nutritional outputs of the compared conventional systems. Due to the non-normal distribution and the small sample sizes in this study, t-tests had to be used over the slightly more accurate z-test. Since it is hypothesised that the production of the food forests will be lower than conventional systems, a one-tailed test was used.

2.5.2.2. Species level

The species level examines the differences between the edible production of a single species in a food forest and in a conventional system. It explores, for example, how many kilogrammes of apples are produced per area in both systems. The harvest data from individual species in the food forests was allocated to the cover of that species in a plot and was then extrapolated to kilogrammes per hectare. Due to the low number of forests that grow the examined species, this analysis is done on a plot-level basis. A forest with multiple plots containing the observed species therefore increased the sample size, making the analysis more reliable.

One-sample two-tailed t-tests were used to analyse the differences between the edible production of single species in food forests and the production of the corresponding species in conventional production systems. Since there was no strong presumption that the production of single species in food forests would be higher or lower than that in conventional systems, a two-tailed test was used to see whether the possible differences were positive or negative.

2.5.3. Factors affecting the edible production of food forests

In order to address sub-question 3, the age, species richness, and canopy cover of the food forests were analysed to see if they affected the edible production at the species level. The age of the food forests was determined in 2023, the species richness was expressed in the combined number of productive and non-productive woody species in a plot, and the canopy cover was considered the cumulative cover of all trees taller than three meters. The relations between the food forests' edible productions and their ages, species diversities, and canopy covers were determined by using the Spearman's rank correlation coefficient. The closer this coefficient reaches 1 or -1, the stronger the positive or negative correlation between the variables is. The analyses were conducted on a plot-level basis, and a minimum sample size of 5 was used to prevent the standard deviation from growing too large. Due to the minimum sample size, raspberry, plum, and walnut production could not be analysed.

3. Results

3.1. The edible production of food forests

The biomass, energy, and nutritional outputs of the monitored forests are shown as a percentage of the average in Figure 1. Mainly due to a lack of time, only eight of the 15 food forests were able to collect a representative amount of data, resulting in a dataset consisting of 22 plots. An overview of the number of plots per forest can be found in Appendix B. Per food forest, the values of the production and nutritional outputs and their averages and standard deviations are shown in Appendix C. On average, the yield values of the monitored food forests are: biomass: 1,284 kg ha^{-1} (st.dev. 817); energy: 948,344 kcal ha^{-1} (st.dev. 807,044); proteins: 12.39 kg ha^{-1} (st.dev. 12.11); carbohydrates: 104.59 kg ha^{-1} (st.dev. 96.79); and fats: 22.13 kg ha^{-1} (st.dev. 44.70).

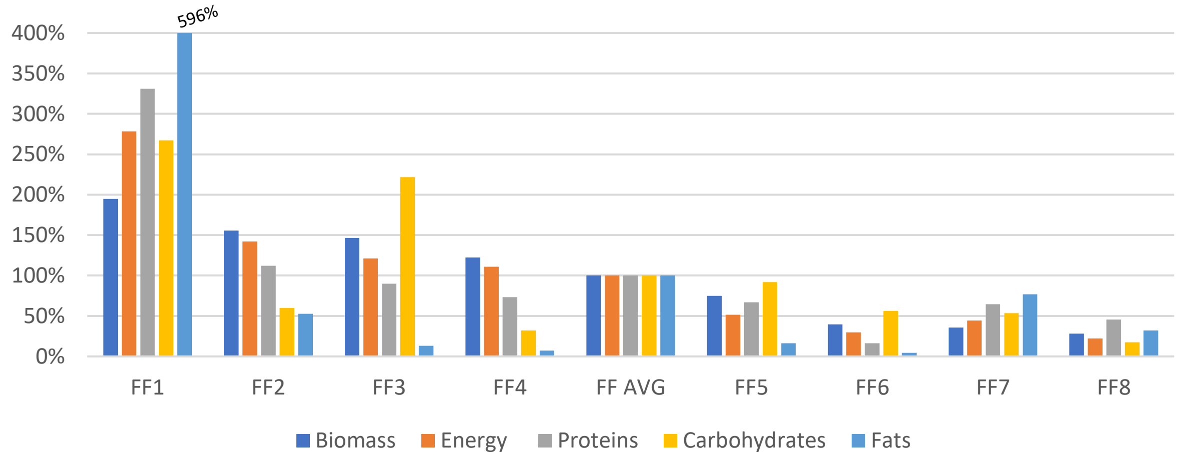

Figure 1. Biomass, energy, and nutritional outputs per food forest as percentage of the average food forest (FF AVG), projected in descending order of biomass production.

The nutrient density, defined as the amount of nutrients per kilogramme of harvest, of the different food forests is shown as a percentage of the average in Figure 2. The corresponding values can be found in Appendix D. It is interesting to see that although FF1 and FF7 have about the same nutrient densities, they have a large difference in total edible production.

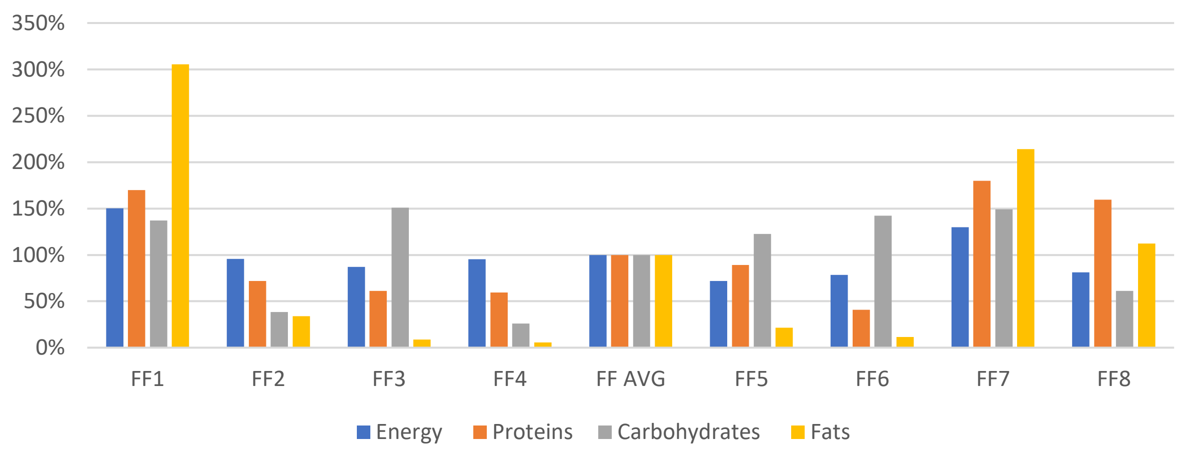

Figure 2. Nutrient densities per food forest as a percentage of the average food forest (FF AVG).

3.2. Food forests in relation to conventional production systems

3.2.1. System level

The average outputs in terms of biomass, energy, and nutrients of the monitored forests, represented as FF AVG, are shown in Table 3, next to the outputs from conventional apple (Elstar and Jonagold), pear, red currant, black currant, hazelnut, and dairy production.

By comparing the averages of the monitored food forests to those of the conventional systems, it can be seen that, except for fat in red and black currant and carbohydrates in hazelnut production, the biomass and nutritional outputs of the monitored food forests are always lower than conventional production systems. Figure 3 shows the outputs of all monitored forests compared to the conventional systems, illustrating that some food forests do have a higher production in terms of biomass, carbohydrates, and fats than some conventional systems. These better-performing food forests are specified in Appendix E.

Table 3. Edible production of the average food forest (FF AVG) and conventional production systems expressed in biomass, energy, and nutritional outputs. Red highlighted values are lower than the food forests average.

	FF AVG	Elstar	Jonagold	Pear	Red currant	Black currant	Hazelnut	Dairy
Biomass (kg /ha)	1.284	32.250	52.500	41.250	13.500	6.000	2.000	17.250
energy (kcal /ha)	948.344	18.060.000	29.400.000	22.687.500	4.860.000	3.180.000	13.400.000	12.247.500
Protein (kg /ha)	12,39	96,75	157,50	82,50	148,50	54,00	328,00	586,50
Carbohydrates (kg /ha)	104,59	3.870,00	6.300,00	4.826,25	594,00	480,00	96,00	759,00
Fat (kg /ha)	22,13	64,50	105,00	123,75	0,00	0,00	1.260,00	759,00

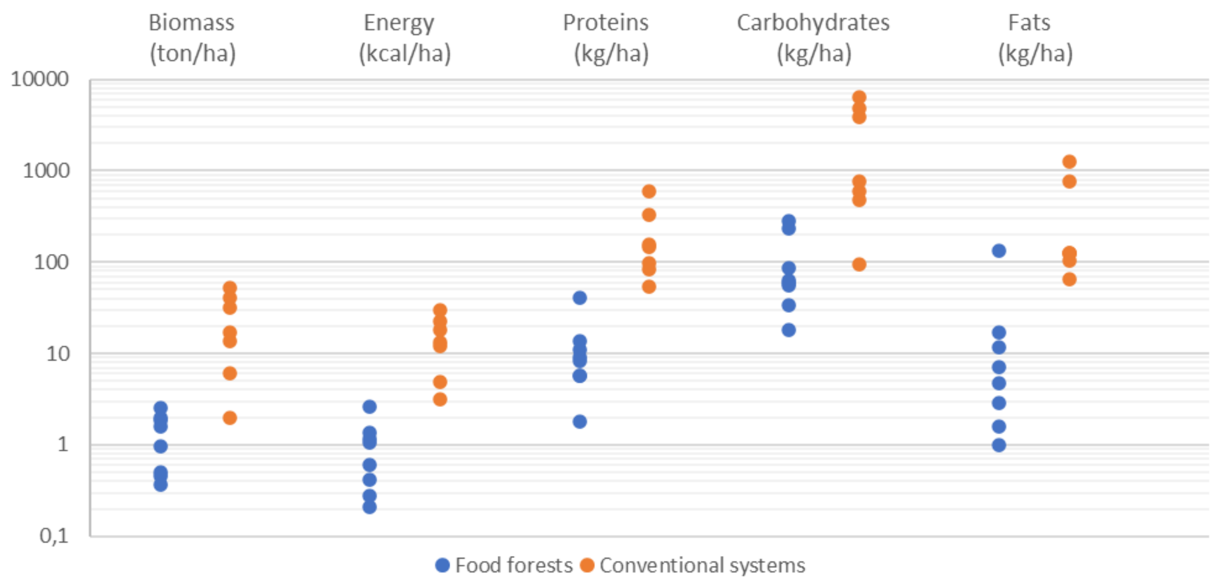

Figure 3. Biomass, energy, and nutritional outputs of the monitored food forests and conventional systems projected on a logarithmic scale. The corresponding values of the food forests can be found in Appendix C and those of the conventional systems in Table 3. The food forests that outperformed conventional systems are specified in Appendix E.

As can be seen in Table 4, except for fat in red and black currant and carbohydrates in hazelnut production, the averages of food forests are in all categories significantly lower ($p < 0.05$) than those of conventional production systems. In all but one case, the difference is even highly significant ($p < 0.01$).

Table 4. Differences in production between food forests' averages and conventional production systems and the resulting p-values. Not-significant p-values (p > 0.05) are shown in red.

		Elstar	Jonagold	Pear	Red currant	Black currant	Hazelnut	Dairy
Energy	Difference (kcal/ha)	-1,7E+07	-2,8E+07	-2,2E+07	-3,9E+06	-2,2E+06	-1,2E+07	-1,1E+07
	P-value	4,7E-11	1,3E-12	8,8E-12	1,3E-06	5,3E-05	4,3E-10	8,5E-10
Protein	Difference (kg/ha)	-84,4	-145,1	-70,1	-136,1	-41,6	-315,6	-574,1
	P-value	1,1E-07	2,5E-09	3,9E-07	3,9E-09	1,3E-05	1,1E-11	1,7E-13
Carbohydrates	Difference (kg/ha)	-3.765,4	-6.195,4	-4.721,7	-489,4	-375,4	8,6	-654,4
	P-value	6,8E-13	2,1E-14	1,4E-13	9,7E-07	5,8E-06	0,40	1,3E-07
Fat	Difference (kg/ha)	-42,4	-82,9	-101,6	22,1	22,1	-1.237,9	-736,9
	P-value	0,02	6,0E-04	1,8E-04	0,10	0,10	7,3E-12	2,7E-10

3.2.2. Species level

The biomass production was for all the examined species at the species level (apple (Elstar and Jonagold), pear, red currant, black currant, and hazelnut) significantly lower ($p < 0.05$) in food forests than in the considered conventional systems, as can be seen in Table 5.

Table 5. Differences in biomass production between food forests and conventional systems regarding apple (Elstar and Jonagold), pear, red currant, black currant, and hazelnut production and the resulting N- and p-values.

	Elstar	Jonagold	Pear	Red currant	Black currant	Hazelnut
Food forests (kg/ha)	8.537	8.537	5.922	4.526	2.958	345
Conv. Systems (kg/ha)	32.250	52.500	41.250	13.500	6.000	2.000
Difference (kg/ha)	-23.713	-43.963	-35.328	-8.974	-3.042	-1.655
Sample size	5	5	7	5	8	5
P-value	1,3E-3	121,5E-6	831,3E-9	0,01	0,01	1,7E-3

The differences between plots growing the same species are visualised in Figure 4. It is striking that for all species, there are large differences between plots of the same forest.

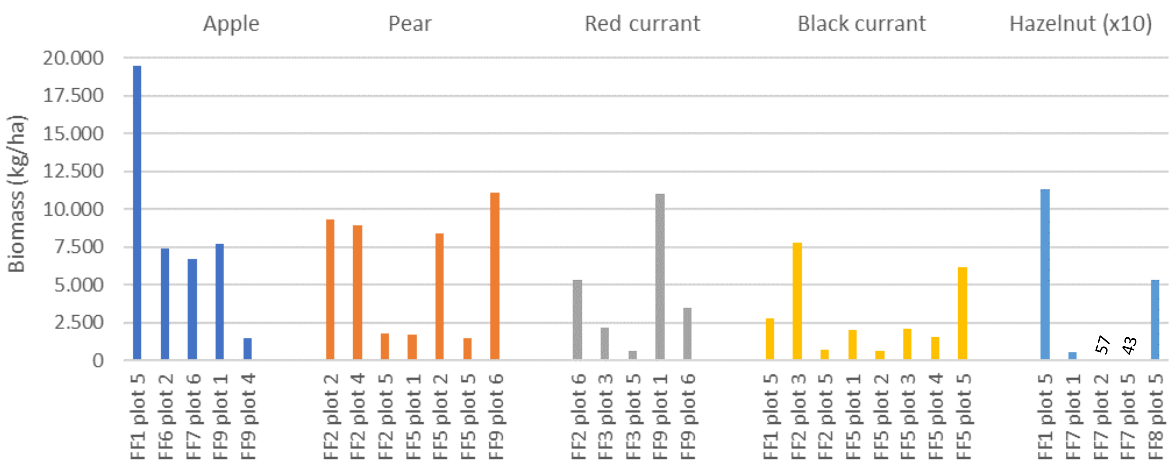

Figure 4. Production per plot for apples, pears, red currants, black currants, and hazelnuts. Hazelnut production is multiplied by 10.

3.3. Factors affecting the edible production of food forests

Next to the comparisons on a system and a species level with conventional production systems, the influence of age, species richness, and canopy cover was analysed. However, none of the three examined factors turned out to be significantly related to the edible production of the food forests. For both age and species richness, the smallest p-value found was 0.16 and for the canopy cover, the smallest p-value was 0.30. An overview of all statistical results can be seen in Appendix F.

4. Discussion

4.1. The edible production of food forests

4.1.1. Nutritional outputs

Large differences in terms of edible production were found within the monitored set of food forests. The most obvious reason for differences in nutritional outputs lies in the differences in total yields per hectare. This can be seen in Figure 1, where the food forests are displayed in descending order of biomass production, whereby the nutrient outputs seem to decrease along the same trend.

An important reason for the variance in biomass production is plant density. FF1, FF2, and FF3 were very densely planted, while FF6, FF7, and FF8 had larger open spaces without production. Visualisations of the forests can be found in Appendix G. The ratio of actively cultivated land for food production and open spaces without production varies strongly among the food forests, which is reflected in the results.

The large differences in nutritional outputs between the monitored food forests and the previous studies (Boulestreau & van Eck, n.d.; Nytofte & Henriksen, 2019; van Eeden, 2020) are remarkable as well. The studies of Van Eeden (2020) and Boulestreau & van Eck (n.d.) score higher nutritional outputs than the forests monitored in this study, as can be seen in Figure 5. It could be argued that this difference likely arises from a different modelling approach. The authors digitally modelled food forests with more productive designs and used conventional production rates, while less production-decreasing factors like yearly fluctuations due to weather conditions were considered.

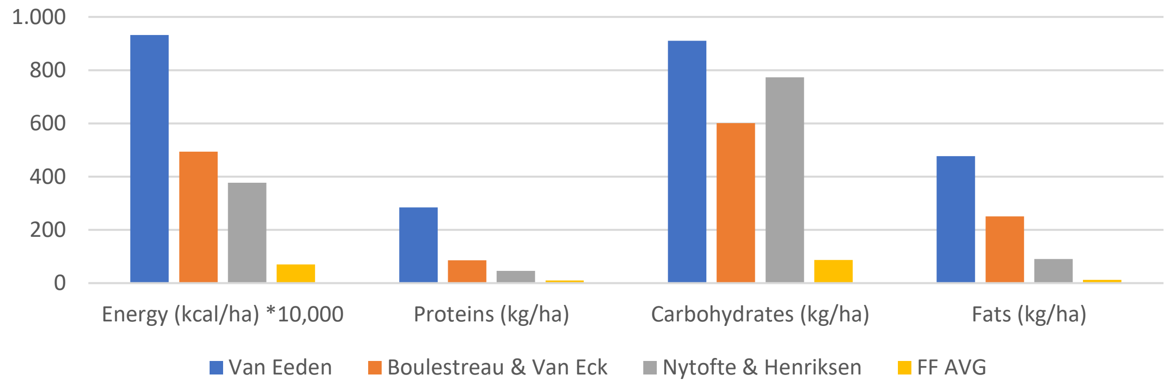

Figure 5. Energy and nutritional outputs of this study (FF AVG) and previous studies. Nytofte & Henriksen derived their through real data collection, Van Eeden and Boulestreau & Van Eck used a modelling technique to derive their data.

The difference with the food forest examined by Nytofte & Henriksen (2019) can be explained by two possible reasons. First is the age of the forest: the forest studied by Nytofte & Henriksen (2019) was 26 years old at the time the study was conducted. Since the average age of the monitored food forests is only 11 years, the production of nuts and many more species is expected to be in a less mature and productive stage of life than the forest studied by Nytofte & Henriksen (2019).

Secondly, forest management is expected to largely influence the production potential of food forests. FF2, FF3, and FF4 (which are food forests with above-average productions in the monitored set of forests) are managed by small groups of people supported by larger groups of volunteers. Below-average-producing food forests, on the other hand, are managed by individuals as side businesses. FF1, which is very similar to the food forest examined by Nytofte & Henriksen (2019), is the exception: this forest is managed as a side business as well, but since it is only of very small scale (0.1 ha) and the manager is specialised in ecological gardening, this food forest still produced above average.

This identified link between management, design, and scale of the food forests and their production output is endorsed by Björklund et al. (2019) and Lovell et al. (2018). Although small and large-scale food forests can be equally productive, it gets increasingly difficult and needs more active management and human involvement for large-scale forests to harvest the full production when a diverse and dense forest design is used. Therefore, Björklund et al. (2019) and Lovell et al. (2018) argue that smaller 'family scale' food forests can increase species richness more easily, whereas larger 'commercial scale' food forests should focus on planting fewer but higher-value species.

Although large differences between the averages of the monitored food forests and previous studies have been identified, the edible production of FF1 (the most productive food forest in the dataset according to Figure 1) is similar to that of Nytofte and Henriksen (2019). This shows that the edible production reached in the study of Nytofte & Henriksen is not necessarily unrealistic for the Netherlands, and over time, similar production may possibly be reached for other food forests as well.

4.1.2. Nutrient density

Although it seems like the nutritional outputs in Figure 1 decrease along the same trend as the biomass production, irregularities in this trend are visible. These irregularities can be explained by the nutrient densities of energy, proteins, carbohydrates, and fats per kilogramme harvested, as shown in Figure 2. The nutrient density is mainly affected by the biomass production and the nutritional values of the species that are present in the plots. The nutrient density of the forest is therefore strongly affected by the species composition.

The presence or absence of nut production is found to have a great influence on the nutrient densities of the monitored food forests. FF1, FF7, and FF8 were the only forests with a considerable amount of nut production (hazelnut and heartnut), which is directly related to the high levels of proteins and fats produced in these forests. Carbohydrate densities are clearly lower in FF2 and FF4 compared to the other forests, which is explained by the absence of carbohydrate-dense species like apple, pear, grape, medlar, and hawthorn in FF2 and FF4, while they are present in the other forests. These findings emphasise the importance of a well-considered species composition, affecting the nutritional outputs and densities of food forests.

Combining the insights of the nutritional outputs and the nutrient densities, it stands out that the nutrient densities of FF1 and FF7 are very much alike and the highest of all forests, while FF1's total edible production is five times higher than FF7's. In both forests, apples and nuts are the dominant species, leading to high nutrient densities. However, FF7 has more and larger low-productive areas, leading to lower overall production. The ratio of open and planted areas and the nutrient densities of the species grown are thus of great influence on the edible production.

4.2. Food forests in relation to conventional production systems

4.2.1. System level

As hypothesised, the monitored food forests have lower edible productions than conventional production systems. An important aspect of the lower production of the food forests in this study, compared to conventional systems, is their design. Since more production-oriented food forests did not meet the selection criteria, the food forests in this study were all romantically designed, in which more attention was given to the natural look and habitat creation through diversification than to high productivity rates. How a food forest is designed is expected to have a considerable influence on its edible production (Björklund et al., 2019). Recently designed food forests are using more intercropping and strip-cropping techniques, which also add to the diversification of the current landscape, while increasingly focusing on higher production rates (Buiter & van Eck, 2018; Den Food Bosch, 2021). It is, therefore, too soon to completely put food forests aside as an option within the agricultural transition.

Studies quantifying the edible production and the impacts on local ecosystem services of more production-focused food forests should be conducted to truly position food forests' edible production in the context of conventional systems.

4.2.2. Species level

As can be seen in Table 5, the production of single species in food forests cannot compete with their conventional counterparts. Specific reasons for these differences cannot be retrieved on the basis of this study. This is because solely a focus was given on the edible production of food forests in the scope of this study. Aspects like the expertise of one specific species in monocultures and artificial tools like pesticides and fertilisers used in conventional systems are assumed to be at the basis of the differences identified.

Even within food forests, different plots have shown different production volumes for a specific species, as can be seen in Figure 4. These differences can partially be explained by the different production rates of the species varieties to which individual trees and shrubs belong (Heijerman-Peppelman & Roelofs, 2010). Since the varieties of the monitored species are mostly unknown, no analysis on that level could be made.

The soil type could have been an influential component as well. However, since FF3 and FF9 both have plots with the highest production rates while also containing very low-productive plots, statements about the relationship between soil and edible production cannot directly be made.

The success of hazelnuts produced in food forests is strongly dependent on the presence or absence of hazelnut borers, whose larvae eat the in-shell hazelnuts. Since the production of hazelnuts in food forests is relatively small, an infected forest often loses all of its production. According to the number of nutshells that was found in FF7, it would have had the highest hazelnut production of all food forests, but due to the borer having affected this forest, it had the lowest. The borer caused trouble in FF9 as well, where the full hazelnut production was considered lost.

These results still give important insights into the potential of hazelnut production in food forests. According to Ton Baltissen, former chair of the Dutch Nut Association, the only solution to hazelnut borers is upscaling beyond the amount that the borer population can eat, since this population seems to have a certain upper limit (personal communications, October 11, 2023). Conventional hazelnut growers are experimenting with pesticides and natural enemies like nematodes, but they don't have the desired success yet.

The high vulnerability of food forests to hazelnut borers has important implications for the long-term potential of food forests. Many advocates of food forests emphasise the potential of future nut production in food forests (Björklund et al., 2019; van Eeden, 2020) and the nutrient densities in this study are strongly affected by nut production as well. But as long as there is no effective measurement against the hazelnut borer, its success cannot be guaranteed. No comparable threats like the hazelnut borer were found for other nut species, but the four times larger presence of hazelnut trees in the monitored food forests compared to walnut trees (50 vs. 13 individuals) acknowledges the significance of the threat.

4.3. Factors affecting the edible production of food forests

The analyses that aimed to find patterns between the biomass production of apples, pears, red currants, black currants, and hazelnuts among the monitored food forests and their age, species richness, and canopy cover have not resulted in significant results. Although no statistically significant results were found, it is not excluded that no patterns in these variables will be found in other sets of food forests. Due to the small sample sizes in these analyses and the heterogeneity of the monitored forests, these analyses should be considered very explorative. If patterns had been found, those could have been starting points for further research to validate them.

The soil type on which the food forests are located would have been an interesting factor to analyse. Initially, the analysis of the soil types was one of the factors that would have been examined. However, due to the lower number of plots with data than initially assumed, the sample sizes of the different types of soil became too small to conduct a reliable analysis.

4.4 Scientific and societal implications

Together with Nytofte and Henriksen (2019), this study forms the basis for quantitative research into the edible production of food forests in the temperate climate zone. Opportunities and needs for future research lie in the multi-year continuation of this study, in-depth case studies, and including production-oriented food forests in these studies. Reflecting on the methods used in this study, it is recommended to monitor as much as possible by yourself since outsourcing to food forest owners resulted in a more than 50% loss of monitored plots. This will, of course, result in more human involvement and higher costs for the study. Therefore, fewer but more in-depth case studies might be of most additional value to the quantitative research into the food production of food forests in the temperate zone.

For farmers that consider starting a food forest, the (highly) significant lower quantified edible production of food forests compared to conventional production systems is not very promising for making viable business plans and might even be daunting. However, an important aspect that is still under addressed and might change farmers attitude towards the less promising results is the productivity of food forests. The productivity shows the ratio of the outputs over the inputs (i.e., the efficiency) of the system and is expected to be higher for food forests than for conventional systems since natural nutrient cycles are utilised and fewer external inputs should be needed (Centeno-Alvarado et al., 2023; Lehmann et al., 2019). In order to allow broad adoption of food forests in the agricultural sector, in-depth (case) studies that monitor all inputs and outputs from the system in order to quantify the productivity and efficiency of temperate food forests are needed.

The position of food forests within the agricultural transition has not drastically changed throughout this study. When agricultural lands are bought up by local governments, there are basically three repurposing options: construction of buildings, extensification of current agricultural activities, or new nature creation (Linders, 2022). Food forests can bridge the gap between the extensification of agriculture and the creation of new nature by mimicking natural ecosystems while producing a considerable amount of food. This amount, the edible production, is, however, expected to be lower than it was expected after previous studies. Moreover, since new nature will probably be managed and maintained by municipalities or provinces, it is unlikely that they will be managed actively, which is expected to negatively affect the edible production potential of food forests. Therefore, the beneficial social and environmental aspects of these food forests might be prioritised over production and financial incentives. Romantic open-picking forests, stimulating local cohesion and returning the not-harvested production back to nature might be of the highest value when managed by local governments.

4.4. Recommendations & considerations

In order to keep contributing to the quantification of the edible production of food forests, it is recommended to continue studying this over multiple years. The continuation of these studies is important for building and improving datasets, for which the generated dataset from this study can act as a starting point. The current dataset contains data for only one season, while fluctuations due to, e.g., weather conditions and mast years can largely influence the production of food forests. By continuing the data collection, the same or additional analyses can be made with, preferably, three- or more-year averages, strengthening the representativeness and reliability of the dataset.

In addition to this study, whose data collection is focused on quantity over quality, more multi-year case studies representing the full edible production of food forests should be conducted. The number of case studies working with real data is still limited to the study of Nytofte & Henriksen (2019) and the very small edible garden study of Björklund et al. (2019). Case studies will be needed for a deeper understanding of the potential and viability of food forests, and specific success factors and hindrances should be addressed (Albrecht & Wiek, 2021b).

A reconsideration of the monitored food forests might strengthen the dataset as well and widen the possible analyses for the continuation of the study. As was found in this study and endorsed by Björklund et al. (2019) and Lovell et al. (2018), the scale and management of food forests are expected to have large effects on their success. Furthermore, a switch from romantically designed food forests to production-oriented forests might better represent the future potential of food forests in the Netherlands. These factors should therefore be considered in the selection procedure of newly monitored food forests in order to make better-substantiated analyses.

Although current food forests produce a significant amount of nutrients, since the bulk of the energy is provided by fruits and nuts, they do not provide a healthy diet (Björklund et al., 2019). Since energy-dense staple crops are lacking, the system is not very conducive to food security. Where Lovell et al. (2018) and Nytofte & Henriksen (2019) recommended to examining facilitating species combinations to increase productivity, it would be interesting to focus this examination on energy-dense crops, possibly shifting towards a somewhat more strip-cropping system.

In order to improve the edible production of food forests, this study suggests focusing on the type of management and the design of the food forest. Both factors are likely to affect each other since an active type of management requires a different design than an inactive type of management. The design mainly includes the species composition and the ratio of productive and non-productive areas. Within the species composition, balances have to be found between productive species and auxiliary species, high and low nutritional species, and species that start producing fruits earlier and later in their lifetime. All these choices are dependent on the way the forest will be managed.

The social and financial aspects of food forests stay understudied and need more attention in future work. Since the focus of to-be-established food forests is on commercialisation (Wartman et al., 2018), feasible financial business cases are the basis for farmers that want to start new food forests. A holistic research into all the costs and benefits of food forests, including social possibilities, would be of high value in risk assessments when starting new food forests. Furthermore, an in-depth analysis and comparison of the subsidies for which food forests and conventional production systems are eligible should be conducted to see if both are financially treated equally and to see where financial hindrances occur and how they can be tackled.

Lastly, to examine how food forests fit in the current nitrogen-sensitive agricultural sector, quantification of the nitrogen-emitting and fixing factors is needed and should be compared with conventional systems and, more importantly, with the type of land use at the place where new food forests may arise.

5. Conclusion

This study aimed to answer the following research question: *What factors influence the edible production of temperate food forests and how does the edible production compare to conventional food production systems?*

By monitoring a unique set of food forests in the Netherlands and Belgium, a dataset containing harvest data from eight food forests, based on 22 plots of 100 m^2, was created. The average values of the plots represent the system of food forests in this study, with an edible biomass production of 1,038 kg ha^{-1} and the following nutritional outputs: energy: 948,344 kcal ha^{-1}; proteins: 12.39 kg ha^{-1}; carbohydrates: 104.59 kg ha^{-1}; and fats: 22.13 kg ha^{-1}.

The production among the monitored forests differed a lot: the edible biomass production ranged from 368 to 2503 kg ha^{-1}. The degree of open space in the forests is likely to be the most responsible factor for these differences. Differences in the nutritional outputs are mainly caused by the nutritional values of the species grown, i.e., the species composition. Both factors are important to be considered in the design phase of to-be-established food forests.

To see how the nutritional outputs of the food forests relate to conventional production systems, they have been compared to conventional apple (Elstar and Jonagold), pear, red currant, black currant, hazelnut, and dairy production in the Netherlands. As expected, food forests produce significantly lower amounts of nutrients than all compared conventional systems. Exceptions are only found for carbohydrates in hazelnut production and fats in red and black currant production. The more natural way of food production in food forests can thus not compete with the conventional way, but it is expected to contribute more to biodiversity and ecosystem services.

At species level, the edible production of apples (Elstar and Jonagold), pears, red currants, black currants, and hazelnuts was found to be significantly lower in food forests than in conventional production systems. Species variety has probably had a large influence on this result, where food forests are more dependent on species varieties that thrive in more natural conditions, while conventional systems grow more high-productive varieties. Furthermore, hazelnut production, and therefore its potential in food forests, is likely to be very sensitive to hazelnut borers since there is a lack of effective pest control.

Age, species richness, or canopy cover are not found to affect the edible production of food forests. However, research into these relationships needs to be reproduced on a larger scale to rule out the relationship between these factors. The type of management has not been analysed but is expected to be a factor that influences the edible production. A definition of different types of food forest management is needed before categorization and research into this relationship can be conducted.

Although the edible production of food forests is relatively low, the nitrogen crisis still offers opportunities for new food forests to be established. By mimicking natural ecosystems, food forests provide ecosystem services while producing a considerable amount of food. The design and management types of food forests are thereby expected to be the most influential on their edible production. At places where arable land may be repurposed for new nature due to the nitrogen crisis, food forests would perfectly fit as a replacement. When the edible production of the food forest, influenced by the scale, design, and type of management, does not allow a viable financial business case, the beneficial social and environmental aspects should be considered.

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Appendices

Appendix A. Nutritional values and sources per product

Table A.1. Nutritional values in kilocalories or grammes per 100 gramme product.

English name	Scientific name	Energy (kcal)	Proteins (g)	Carbohydrates (g)	Fats (g)	Source
Almond	Prunus dulcis	622	25,4	5	53,4	[1]
Apple	Malus	56	0,3	12	0,2	[1]
Autumn olive	Elaeagnus umbellata	90,8	4	13,6	2,3	[5]
Barberry	Berberis	30	0	8	0	[4]
Black berry	Rubus subg. Rubus	37	0,9	5,1	0,1	[1]
Black currant	Ribes nigrum	53	0,9	8	0	[1]
Chestnut	Castanea	189	4	35	2,7	[1]
Chokeberry	Aronia	55	1,5	10,9	0,2	[4]
Dogwood	Cornus	44	1	10,5	0,2	[4]
Elderberry	Sambucus	70	0,7	18,3	0,5	[3]
Golden currant	Ribes aureum	36	1,1	4,4	0	[1]
Gooseberry	Ribes uva-crispa	49	0,9	9	0	[1]
Grape	Vitis vinifera	78	0,6	16,8	0,2	[1]
Hawthorn berry	Crataegus	102	0,5	25,1	0,6	[7]
Hazelnut	Corylus avellana	670	16,4	4,8	63	[1]
Heartseed walnut	Juglan ailantifolia	584	23,9	14,3	54,2	[6]
Jostaberry	Ribes nidigrolaria	54	0,8	11,1	0,7	[3]
Kaki persimmon	Diospyros kaki	77	0,5	18,6	0	[1]
Medlar	Mespilus germanica	50	0,2	10,6	0,2	[1]
Pear	Pyrus	55	0,2	11,7	0,3	[1]
Plum	Prunus domestica	40	0,8	7,3	0	[1]
Quince	Cydonia oblonga	69	0,5	1,5	0,1	[2]
Raspberry	Rubus idaeus	37	1,4	4,5	0,3	[1]
Red currant	Ribes rubrum	36	1,1	4,4	0	[1]
Redflower currant	Ribes sanguineum	36	1,1	4,4	0	[1]
Rosehip	Rosa	95	3,5	19,5	0,1	[2]
Walnut	Juglans regia	706	15,9	5,1	68,1	[1]
White currant	Ribes rubrum alba	36	1,1	4,4	0	[1]

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Appendix B. Number of plots per food forest

Table B.1. Number of plots per forest that initially would have been and really has been monitored.

Name	Initial plots	Monitored plots
FF1	2	1
FF2	4	1
FF3	2	2
FF4	4	3
FF5	6	6
FF6	2	2
FF7	5	5
FF8	4	2
FF9	6	0
FF10	6	0
FF11	2	0
FF12	4	0
FF13	2	0
FF14	4	0
FF15	2	0
Total	**55**	**22**

Appendix C. Nutritional outputs per food forest

Table C.1. Biomass, energy, and nutritional outputs per food forest. Also visualised as percentage of the average in Figure 1.

Name	Biomass (kg/ha)	Energy (kcal/ha)	Protein (kg/ha)	Carbohydrates (kg/ha)	Fat (kg/ha)
FF1	2.503	2.640.160	41,03	279,60	131,87
FF2	2.003	1.347.524	13,87	62,71	11,69
FF3	1.885	1.150.811	11,15	231,74	2,89
FF4	1.576	1.052.943	9,07	33,57	1,57
FF5	963	486.756	8,30	96,13	3,58
FF6	509	279.287	1,79	58,86	0,99
FF7	461	419.173	8,25	55,77	17,28
FF8	368	210.101	5,66	18,31	7,13
FF AVG	**1.284**	**948.344**	**12,39**	**104,59**	**22,13**
st.dev.	817	807.044	12,11	96,79	44,70

Appendix D. Energy and nutrient densities per food forest

Table D.1. Energy and nutrient densities of the monitored food forests and their averages. Also visualised as percentage of the average in Figure 2.

	Energy (kcal/kg)	Protein (g/kg)	Carbohydrates (g/kg)	Fats (g/kg)
FF1	1.054	16,4	111,7	52,7
FF2	672	6,9	31,3	5,8
FF3	611	5,9	122,9	1,5
FF4	668	5,8	21,3	1,0
FF AVG	702	9,7	81,5	17,2
FF5	505	8,6	99,8	3,7
FF6	550	3,9	115,9	2,0
FF7	911	17,4	121,5	36,9
FF8	571	15,4	49,8	19,4

Appendix E. Food forests compared to conventional systems: exceptions

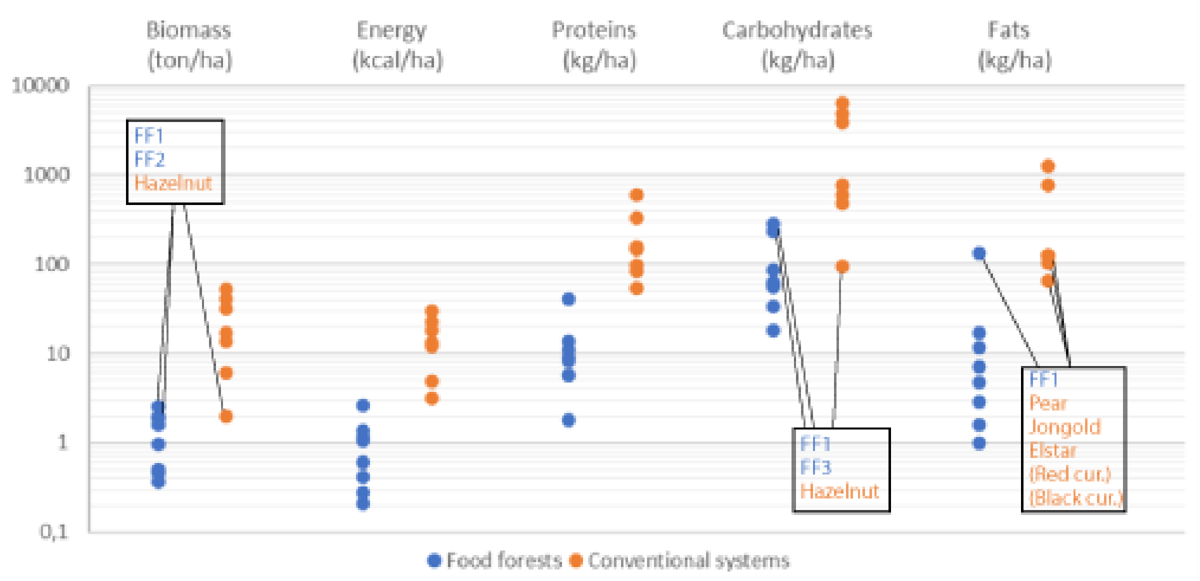

Figure E.1. Biomass, energy, and nutritional outputs of the monitored food forests and conventional systems projected on a logarithmic scale. Food forests that outperformed conventional production systems are specified. Species mentioned in brackets are not shown in the figure due to a 0-value. The corresponding values of the food forests can be found in Appendix C and those of the conventional systems in Table 3.

Appendix F. Statistical results age, species richness, and canopy cover

Table F.1. Statistical results of the relationship between the age and biomass production of apples, pear, red currants, black currants, and hazelnuts in food forests.

	Apple	**Pear**	**Red currant**	**Black currant**	**Hazelnut**
Spearman rank correlation	-0,67	0,00	0,58	-0,30	-0,87
Sample size	5	7	5	8	5
P-vlaue	0,25	1,00	0,31	0,45	0,16
Significance	**NO**	**NO**	**NO**	**NO**	**NO**

Table F.2. Statistical results of the relationship between the species richness and biomass production of apples, pear, red currants, black currants, and hazelnuts in food forests.

	Apple	**Pear**	**Red currant**	**Black currant**	**Hazelnut**
Spearman rank correlation	0,15	-0,20	-0,20	0,23	0,87
Sample size	5	7	6	8	5
P-vlaue	0,77	0,64	0,80	0,57	0,16
Significance	**NO**	**NO**	**NO**	**NO**	**NO**

Table F.3. Statistical results of the relationship between the canopy cover and biomass production of apples, pear, red currants, black currants, and hazelnuts in food forests .

	Apple	**Pear**	**Red currant**	**Black currant**	**Hazelnut**
Spearman rank correlation	-0,50	0,07	0,50	0,05	-0,60
Sample size	5	7	5	8	5
P-vlaue	0,37	0,87	0,37	0,90	0,30
Significance	**NO**	**NO**	**NO**	**NO**	**NO**

Appendix G. Visualisation of the monitored food forests

This section has been removed due to privacy-sensitive information.

Edible production potential of food forests in the temperate zone

January 2024

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