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Master thesis

The contribution of food forests towards a sustainable food system: Current state and potential in Europe

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Abstract

Food forests are multifunctional perennial polyculture systems that use the structure and functions of a natural forest as a model to cultivate a diverse range of edible plants. They represent an agroforestry practice that has the potential to combine the ecological, social-cultural, and economic benefits of forest ecosystems and agricultural systems in one area. This study provides a comprehensive overview of the current state of food forests in the temperate climate of Europe by presenting collected data from 30 food forests, expert interviews, and site visits. The findings highlight the potential but also the limitations of food forests to create a more sustainable food system while contributing to the United Nations' Sustainable Development Goals (SDGs). A total of 9 SDGs was found to be positively influenced by the effects of food forests, such as soil, water and biodiversity conservation, adaption to climate change and contribution to community well-being. Additionally, the study addresses challenges related to management, social acceptance, and economic efficiency of food forests, and provides guidance for financing and scaling up these systems, as well as promoting their wider adoption into mainstream. The information gathered in this study can be used by food forest entrepreneurs to improve their planning and management processes, enabling them to maximize the benefits of this innovative and promising approach to agriculture.

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List of Abbreviations

CAP	Common Agricultural Policy
EC	European Commission
EM	Effective Microorganisms
EU	European Union
GHG	Greenhouse gas
MoI	Means of Implementation
SDGs	Sustainable Development Goals
UN	United Nations

1 Introduction

The global food system is responsible for a significant proportion of the environmental and social challenges facing humanity today. In recent decades, food in large parts of Europe has become as cheap and readily available as never before at any time in history, but not without consequences (Godfray et al. 2010).

The high demand for food and other products resulted in an extensive transformation of landscapes caused by the expansion of agricultural production systems, urban areas and commercial infrastructure (Hooke et al. 2013, Poschlod 2017). Expansion has been accompanied by a spatial separation of land-use systems, that are maximized towards the supply of one or few ecosystem functions and services. This spatial separation resulted in agricultural land-use systems that are adapted to machine processing and intensive cultivation of single species, but rely on high external inputs, such as mineral fertilizers and pesticides. They are characterized by an overall low biodiversity and therefore represent an ecosystem that is particularly vulnerable to the effects of climate change (Altieri et al. 2015, Hölting et al. 2019, O'Farrell and Anderson 2010). This vulnerability also extends to the global food system as a whole (Wheeler and Von Braun 2013). Nevertheless, agriculture remains the main driver for soil degradation and loss of biodiversity, and is responsible for approximately three quarters of the produced greenhouse gas (GHG) emissions within the global food system (Tubiello et al. 2021). The global food system itself produced an estimated 16 tons of CO2-eq. in 2018, the equivalent of one-third of the global anthropogenic GHG emissions, mainly due to the impact of industrial agriculture and globalized food supply chains (Garnett 2011, La Trobe and Acott 2000, Tubiello et al. 2021).

The need of introducing alternative systems is well known and already integrated in the agenda of several international programs, such as the Sustainable Development Goals (SDGs), formulated by the United Nations (UN) (Sachs 2015). The SDGs consist of 17 interlinked targets that call for immediate action to combat climate change, end poverty, and ensure prosperity and peace for all people by 2030 (UNDP 2023). The performance of the global food system is inevitably linked to at least 12 of the 17 SDGs (Chaudhary et al. 2018, Viana et al. 2022). Correspondingly, its performance plays a crucial role in achieving the goals set within the SDGs as a whole, especially in regard to adapting to climate change (Clark et al. 2020).

Creating a resilient and sustainable food system appropriate for future generation requires a radical transformation of both, the agricultural production systems and the human diet (Foley 2011, Willett et al. 2019). Reversing the spatial segregation between agricultural systems, urban areas and natural ecosystems towards multifunctional land-use systems that combine the derived ecosystem services from all systems is thought to increase the ecological resilience and the overall benefits that society can obtain from an ecosystem (Brandt and Vejre 2004, FAO 2000b, O'Farrell and Anderson 2010, Otte et al. 2007). The combination of woody perennials and agricultural systems, so called agroforestry, is thereby recognized as a valuable tool for achieving global climate targets and creating sustainable multifunctional landscapes (Kay et al. 2019, Santoro et al. 2020, Veldkamp et al. 2023, Wilson and Lovell 2016). The potential benefits of agroforestry systems, such as carbon sequestration, conservation of biodiversity and wildlife, water and soil conservation, microclimate regulation, nutrient recycling and erosion control, are well documented (Jacobs et al. 2022, Jose 2009, Kim et al. 2016, Lovell et al. 2018, Torralba et al. 2016, Tsonkova et al. 2012, Veldkamp et al. 2023). Food forests or forest gardens describe specific agroforestry systems, which primarily consist of edible perennial plants.

A food forest or forest garden is a multi-layered perennial polyculture system, which uses the structure and functions of a natural forest as a model to cultivate a complementary diversity of edible plants. It is carefully designed and managed in a way that aims to maximize mutually beneficial relationships and interactions between individual plants (Crawford 2010, Park et al. 2018). The goal is to obtain a high combined harvest of different products with low-maintenance and low-input management, while the services of a natural ecosystem, e.g. the sequestration of carbon, purification of air and water or climate regulation, are maintained (Jacke and Toensmeier 2005). The harvest from the perennial plants, such as nuts, fruits, herbs, leaves, or berries represent the main agricultural crops in a food forest or forest garden. Their additional harvest consists of wood related products, similar to other agroforestry systems. It is assumed that food forests or forest gardens do not only provide ecological benefits, but also enhance the social-cultural services of landscapes by supporting community well-being and the development of ecological literacy (Albrecht and Wiek 2021a, Hammarsten et al. 2019, Wartman et al. 2018). They present a multifunctional land-use system with the potential to transcend the traditional nature-culture dichotomy and create a balance between production and ecosystem services (Wiersum 2004).

Between the terms “food forest“ and “forest garden“ there is little distinction in research and practice (Albrecht and Wiek 2021a). While forest gardens were first mentioned in the United Kingdom (UK) in the 1980s, the idea of food forests emerged at about the same time within the permaculture movement in Australia (Albrecht and Wiek 2021a, Hart 1996, Mollison et al. 1981). Some authors and practitioners suggest that a distinction between both terms would be reasonable (Albrecht and Wiek 2021a). A food forest in this sense should refer to the “forest scale“, whereas a forest garden would be limited to the “garden scale“. Considering the definitions of a forest ecosystem, a food forest should therefore be defined by a minimum size/area of 0.5 ha and a canopy cover of at least 10% in order to provide forest-like ecosystem services (Albrecht and Wiek 2021a, Chazdon et al. 2016, FAO 2000a). However, as the whole topic of food forests and forest gardens is still at a pioneer stage and little distinction between the two has been made until recently, this study includes both food forests and forest gardens, but uses the term “food forest“ for both systems in the following. This way it can be ensured that interesting cases of smaller size are not excluded and the overall potential of these systems can be assessed more comprehensively (Albrecht and Wiek 2021a).

Recently, peer-reviewed and non-academic research about temperate food forest systems is gaining momentum, alongside an increasing number of projects being implemented (Wartman et al. 2018). However, their potential contribution towards a sustainable food system remains poorly studied, as they are often just described as a sustainable practice for self-sufficiency, ecological restoration or cultural transformation (Albrecht and Wiek 2021a, Park et al. 2018, Wartman et al. 2018).

The aim of this research is to partly fill this knowledge gap and determine to what extent food forests can help in creating a sustainable food system in temperate Europe.

To achieve this, the following research objectives are adopted:

A. Identification of the main services and characteristics of food forests.

B. Evaluation of the sustainability of food forests in the light of the Sustainable Development Goals proposed by the United Nations.

C. Identification of factors that influence the potential contribution of food forests towards the food supply in Europe.

To investigate these research objectives a qualitative research approach was applied, including data collection through semi-structured interviews with experts and food foresters as well as on site visits. Gathering information from previous publications and observing real-world applications over an extended period of time was necessary to get a holistic overview of the research topic. Food forests can differ drastically from site to site, and in order to fully understand the numerous interrelations between food forests and a sustainable food system, many factors have to be considered.

2 State of the art

A crucial part in this consideration is the comprehensive understanding of the underlying structure and mechanisms of food forests. The state of the art aims at providing this information by describing the origin and core principles of food forests. Based on the state of scientific knowledge in ecology, the described principles also include instructive recommendations that can be used for food forest implementation and management. Furthermore, a classification of food forests into the context of agroforestry systems is established in this section. This classification should not be seen as a final state, but rather as a first foundation that aims to encourage further scientific debate regarding the topic.

2.1 Origin

Since the settlement of humans, their surrounding landscape has constantly been influenced and shaped by their needs to create land-use systems that cover the requirements for their livelihood. Modifying the forest or mimicking natural processes in order to obtain food and other products is, together with shifting cultivation, arguably the oldest form of human land use systems (Belcher et al. 2005, Kumar and Nair 2004). Indigenous North Americans perceived themselves as an integral part of the forest and intentionally created agroecosystems to alter the production of forest products and their own crops (Soemarwoto and Conway 1992). The Javanese homegardens of Indonesia, a diverse, multi-story combination of trees, shrubs and other crops around the household, are thought to be at least 10,000 years old and likely present the first role model for the creation of modern food forests (Hutterer 1982, Nair et al. 2021b). Mimicking of natural forests in the Javanese homegardens is thought to have occurred accidentally through an expansive natural and artificial selection of plants (Soemarwoto and Conway 1992). The use of homegardens as an integral part of the farming system has a long agricultural tradition and is still widely distributed, especially in tropical regions (Kumar and Nair 2004).

In Europe, the first documented “vertical mixed cropping“ systems were found in the Mediterranean regions and consisted of a combination of food, fuel or fodder trees together with vines and arable crops (Desplanques 1959, Lavignac and Audiot 2001, Meynier 1958, Paris et al. 2019, Stanislawski 1969, von Babo 1866). These systems were often characterized by rows of vines trained onto fuel, fodder or fruit trees, similar to what is often found in modern food forests.

Figure 1 Vertical layers in the food forest of B. Gruber. Left: *Rubus phoenicolasius* as vertical layer. Right: *Vitis vinifera* on *Malus domestica* (own image)

In central Italy, the emergence of these systems, can be dated back to the age of the Etruscans (900 BC – 27 BC). These so called "*coltura promiscua*" (mixed cultivation) dominated the landscape until land consolidation took place during the 20th century (Desplanques 1959, Pinto-Correia and Vos 2004, Poschlod 2017). It is estimated that these multifunctional "landscapes of trees" produced more than 50% of the generated timber and wood in Italy until 1950 (Meynier 1958, Mezzalira 1999, Paris et al. 2019). The complexity of these systems in terms of plant diversity and involved plant layers, however, is lower compared to the tropical homegarden (Nair et al. 2021b).

In the temperate regions of Europe a highly diverse and multilayered homegarden, like it can be found in the tropics, was first mentioned by Robert Hart in the 1980s. Inspired by the tropic model, Hart started to experiment in his own 500 m^2 garden, planting a dense structure of different tree and shrub species (Hart 1996). Even though too many species were planted too close together, leaving the understory dark and unproductive after some years, the documentation of his experiences inspired further practitioners in the temperate climate (Crawford 2010, Douglas and Hart 1976). More food forest pioneers, either inspired by Hart or own experience in the tropics, followed to experiment with the design of temperate food forests. Until today, the food forest movement in Europe developed towards an own agricultural practice, which is increasingly utilized apart from households and beyond the “garden scale“ (Green Deal 2017).

2.2 Classification

A universally acceptable or applicable classification for the different types of agroforestry systems does not exist to date (Nair et al. 2021a). Similar systems are often categorized under different names depending on their country or continent of origin. However, they can be classified based on the nature and arrangement of their components. It can be differentiated between three general types of agroforestry, which derive from the three basic components that can be managed within an agroforestry system: “The tree or woody perennial, the herb (agricultural crops including pasture species), and the animal.“ (Nair et al. 2021a). According to theses major components, McAdam et al. (2009) classify the following non-mutually exclusive systems for Europe:

1. Arable agroforestry where crops are integrated with trees (Silvoarable). The three subcategories are crops combined with (a) permanent woody crops, (b) woodlands (>10% tree cover), and (c) range-lands with sparse trees.

2. Livestock agroforestry where livestock production is integrated with trees (Silvopastoral). The four subcategories are: livestock combined with (a) permanent woody crops, (b) woodlands, (c) arable lands with sparse trees, and (d) grasslands with sparse trees.

3. High-value tree agroforestry where the primary land use is permanent woody crops such as fruit orchards, olive groves, and nut trees. The two subcategories are (a) grazed and (b) intercropped.

To date, no classification of food forests into the context of agroforestry systems has been made. This might be due to the fact that since the concept of agroforestry emerged in the 1970s, most research focused on the incorporation of trees into agricultural cropping systems, while the incorporation of crops into forest systems has only recently been given more emphasis (Malézieux 2012, Wiersum 2004). Therefore, the creation of a uniform food forest definition has not been part of scientific or political debate. With an increased interest in these systems today, a first governmental definition for food forests in Europe has been established recently in the Netherlands as part of the implementation of the "*European Green Deal*", which is a concept by the European Commission (EC) with the aim to reduce net GHG emissions in Europe to zero until 2050 (EC 2019, Wartman et al. 2018). The resulting "*C-219 Green Deal Voedselbossen*" is a legislation in the Netherlands to allocate funding from the CAP for food forest implementation and management. Within this legislation, food forests are defined by the following characteristics (Green Deal 2017):

- A human-made productive ecosystem modeled on a natural forest
- High diversity of perennial and/or woody species
- Presence of a canopy layer
- Presence of at least three other vegetation layers of e.g. lower trees, shrubs, herbs, ground covers, underground crops or climbing plants
- Presence of a rich forest floor life
- No tillage, no use of mineral fertilizer and synthetic pesticides
- Minimum size of at least 0.5 hectares in an ecologically rich environment or minimum size of 20 hectares in a severely depleted environment

These characteristics were created for large food forests with a primary focus on food and timber production and are therefore not transferable to urban food forests. Although some of the characteristics, such as the presence of a rich forest floor life, remain unclear and difficult to measure, they can assist in classifying food forests within the context of agroforestry systems.

According to the classification by McAdam et al. (2009) mentioned above, food forests with these characteristics can be defined as diverse high-value tree agroforestry systems, where perennial plants are the main management component. However, other high-value tree agroforestry systems in Europe, such as orchards or olive groves, show less complexity and diversity than food forests (Nair et al. 2021). As the initial idea of food forests originated from tropical examples it seems more appropriate to compare food forests with agroforestry practices in the tropics that mainly consist of perennial crops. According to Nair et al. (2021a) these include: Homegardens, Forest farming, Shaded perennial-crop systems and Multipurpose tree gardens. Forest farming should be distinguished from the other practices, because in this specific case an already existing forest is optimized for food production and not planted from the bottom up. In the matured state, however, the different systems are very similar to one another in terms of the design and selected plant species. Like food forests in temperate climate, they all mimic the structure and functions of a natural forest for agricultural production. As this system is not comparable to traditional agroforestry systems in Europe, which are classified by McAdam et al. (2009), food forest should be distinguished from these.

It can therefore be concluded that food forests should be classified as an own subcategory of high-value tree agroforestry systems due to their extended complexity and diversity compared to similar systems in Europe. According to the "*C-219 Green Deal Voedselbossen*" the main characteristic of food forests is their design based on a natural forest ecosystem as a role model. Describing this characteristic with the presence of at least four vertical layers consisting of perennial and edible plants can define the new subcategory. Thereby forest gardens, urban food forests or similar systems of smaller size are not excluded from this subcategory, but a clear differentiation between less complex high-value tree agroforestry systems is established. Within the new subcategory it can then further be distinguished between forest gardens, urban food forests and other similar systems, such as forest farming, under the consideration of already existing definitions (Albrecht and Wiek 2021a, Bruhn et al. 2009, Green Deal 2017, Munsell et al. 2021). Useful characteristics for the further classification of such systems are the size, the presence of a canopy layer and the location. However, with this new subcategory, which can be called "natural forest ecosystem for agricultural production", food forests and similar systems can be integrated within the existing classification of McAdam et al. (2009) for agroforestry systems in Europe.

2.3 Core principles of food forests

2.3.1 Design and structure

When designing food forests or other agricultural systems, it is necessary to observe all influencing factors carefully and precisely before starting with the implementation process. Observations and research on climate, soil conditions and site characteristics, wind directions, sun paths, natural surrounding flora and fauna as well as the available water supply have to be considered. The surrounding community and markets also provide important information and determine the selection of design elements. As food forests change greatly over their lifetime, observations should be continued after the implementation and the design adapted if necessary (Jacke and Toensmeier 2005).

Food forests try to mimic the structure of natural forests but must be designed with a relatively open canopy when planted in the temperate climate. The solar radiation in temperate food forests is, in contrast to areas close to the equator, normally the limiting factor of production (Malézieux 2012). While food forests in the tropics are mimicking a late-succession or old-grown forest, in temperate climates the canopy in the matured stage has to be maintained as a young or mid-succession-stage forest (Belcher et al. 2005, Michon et al. 2000). This allows enough radiation to pass through to the lower vegetation layers (Crawford 2010). Since the settlement in Europe, the landscape was constantly shaped by humans, leading to only small areas remaining comparable to a natural forest ecosystem (Poschlod 2017). Most of the forests that can be found in Europe nowadays are managed industrial forests with a dense canopy, which do not present the role model of a food forest (EAA 2022a).

The selection of different plant compositions determines the final structure of a matured food forest. To achieve a desired self-regulating and self-sustaining ecosystem, edible species and functional species, like nitrogen fixing or pollinator attracting plants, are combined in the same design. The plants that are used are mainly perennial, assume multiple functions and contain a selection of all different vertical layers of a natural forest. The objective of the multi-layered structure of a food forest or forest garden, both above- and belowground, is to increase the efficiency of capturing light, water and nutrients within a productive ecosystem (Crawford 2010).

Crawford (2010) classifies seven vertical layers including medium-to-large canopy trees (>10 m), small trees and large shrubs (4-9 m), small shrubs (<3 m), herbaceous perennials (<3 m), ground cover plants, climbers and underground crops. Because even more layers can be found in a natural forest, some authors differentiate between up to 12 layers (Gruber 2021). Since designed food forests do not necessarily need to contain plants from all possible layers and due to the difficulty of clearly differentiating between each layer, it seems adequate to simplify natural complexity and categorize between four layers in a food forest (Fig. 1) (Jacke and Toensmeier 2005, Whitefield 2002).

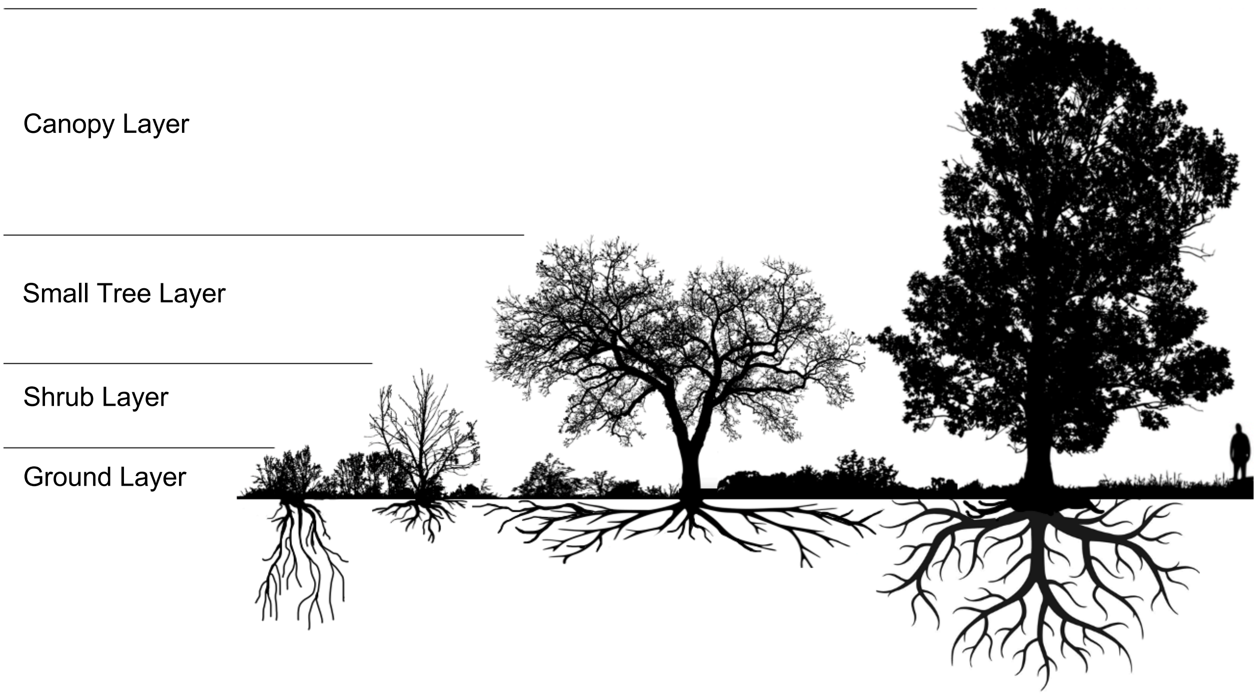


Figure 2 Schematic illustration of the stratification of a four layered food forest above- and belowground (Own illustration)

Besides the open canopy and multiple plant layers, the structure of food forests is characterized by the occurrence of special habitats and different microclimates to enhance the overall biodiversity of the system (Jacke and Toensmeier 2005). However, further explanation of general design strategies would go beyond the scope of this study. Detailed information on food forest design is already provided by various authors, which often describe them as a system for self-sufficiency, ecological restoration, or recreation (Crawford 2010, Jacke and Toensmeier 2005, Kranz and Deemter 2021, Weiss and Sjöberg 2018, Whitefield 2002).

2.3.2 Functional diversity

The relationship between species richness and ecosystem productivity and stability is an important subject of debate in ecological science (Fraser et al. 2015, Grace et al. 2016, Loreau and Hector 2001, Willig 2011). It is generally accepted that a higher species richness above- and belowground is associated with increased biomass production in plant communities and thereby positively influences ecosystem productivity and stability (Altieri 1999, Eisenhauer et al. 2017, Malézieux 2012, Tilman 1999). Even though the positive interactions between ecosystem functions and species richness have been shown in various studies, it is assumed, that the functional trait composition of biological communities, so called functional diversity, usually explains ecosystem functioning better than species richness alone (Balvanera et al. 2006, Hooper et al. 2005, Tilman et al. 2006, Violle et al. 2007). The functional traits of species describe their ecological role and how they interact with the environment and other species (Díaz and Cabido 2001, Tilman 2001). A group of species that occupy similar niches and have similar effects on ecosystem processes is called functional group.

The positive influence of high species richness on ecosystem functions is therefore often explained by the occurrence of complementary effects between functional groups, such as niche partitioning or interspecific interaction (Cardinale 2011, Cardinale et al. 2002, Mason et al. 2005, Tilman et al. 1997). A high diversity of species that occupy different niches, enhances the effectiveness of resource acquisition, and decreases the competition among species (Naeem et al. 1994).

Therefore, the selection of plants for food forests should consider a high functional and structural diversity rather than only a high taxonomic diversity. Different functional groups react individually and asynchronous to different disturbance factors and can thereby influence the resilience of the system against environmental fluctuations or pests and diseases (Altieri 1999, Malézieux 2012). In a diverse system, supposing that the environmental conditions change over time and a functional group cannot maintain its function anymore, another group, which has only been occupying a small niche before, might be able to step in place and maintain the ecosystem functionality (Ebeling et al. 2014). As different plant species also attract different animal species, a more diverse and balanced nutrient input through their excretions can be ensured (Schuldt et al. 2019).

A high functional diversity in the food forest can partly be ensured through a high structural diversity, which means a high variation in the habitat's architecture above- and belowground through plants from all different layers of a natural forest (Jacke and Toensmeier 2005). Besides the spatial separation in different layers, a temporal separation in vegetation growth and cycling can also be used to minimize the competition for habitat, light and nutrients and ensure a high functional diversity. Belowground nutrient and water uptake by plants is influenced by the root system, the periodicity of root growth and activity in relation to the species demand as well as the environment and can thus be optimized through planting the right species composition (Atkinson and Wilson 1979).

The open design of a food forest furthermore creates zones comparable to forest edges, which generally allow the use of a higher species diversity (Franklin et al. 2021). Geomorphological heterogeneity of landscapes is linked to higher plant species richness and can therefore also be used in the food forest design to create more niches, which in turn can be used by more diverse functional groups (Burnett et al. 1998, Nichols et al. 1998). Within homogenous landscapes, which were formed in Europe during the land consolidations, especially in the second half of the 20th century, certain areas can be mechanically modified once before planting (Poschlod 2017).

2.3.3 Soil fertility

Soil fertility is the foundation of every terrestrial ecosystem and determines its productivity, making it the most important pillar for human nutrition (Wall et al. 2015). An increase in soil fertility is closely linked to biodiversity and enhances the productivity of ecosystems and their resilience to disturbances like weather extremes or pests and diseases by enhancing the nutrient and water supply of the soil (De Ruiter et al. 1995, Nielsen et al. 2015, Wagg et al. 2014). Soil fertility is strongly dependent on the soil type and the amount and diversity of soil organisms.

These organisms can range in size from bacteria, protozoa and single-cell algae, or fungi to more complex invertebrates like earthworms or nematodes, insects, small vertebrates and plants. Together these organisms make up the soil food web. They are involved in nutrient cycling, bioturbation and humus accumulation and determine soil functioning and its delivered ecosystem services (De Vries et al. 2013, Edwards and Bohlen 1996, Hunt et al. 1987, Wagg et al. 2014). As they are dependent on the energy that derives from primary producers, they are strongly influenced by the prevailing land use system (De Vries et al. 2013). There is evidence that plants shape the composition of microbial communities, likely through root exudates, in order to enhance their own nutrition supply (Badri and Vivanco 2009, Jacoby et al. 2017). Results from a grassland experiment by Eisenhauer et al. (2017) even suggest, that plant diversity enhances soil microbial biomass by increasing root-derived organic inputs.

According to this, the composition and processes of the soil food web are influenced by the amount and the composition of primary producers colonizing the area and the corresponding generated organic material. Soils in the food forest are therefore mostly covered either with mulch or living plants not only to maintain a constant nutrient supply, but primarily to supply energy for the soil food web. The distribution of leaf surface in the vertical layers of the living plants aims to maximize the photosynthetic performance. Sugars and amino acids from the assimilation process are integrated again in the soil nutrient cycle and ensure a good energy supply for the soil food web, which correspondingly leads to soil enhancement (Schubert 2017).

A constantly covered soil also reduces the evaporation rate of the soil, thereby enhancing its water efficiency, and simultaneously providing a natural protection against water and wind erosion (Descroix et al. 2001, McMillen 2013). Mulch material is naturally produced by the food forest itself after the establishment phase, but turnover rates can be enhanced by pruning and chopping of organic material. During the establishment phase, processes can be initiated through feeding the soil food web with organic compounds including manure, plant residue, compost or compost teas. However, the influence of fertilizer on the long-term development and health of trees remains scientifically unknown.

Annual cropping systems are inevitably linked with soil tillage, which disturbs the soil food web and adversely influences soil structure and properties (Kladivko 2001, Tebrügge and Düring 1999). As food forests are deciduous polycultures with a constant soil cover, there is no necessity of tilling the soil after the initial planting, which in the long-term leads to enhanced conditions for soil biota, humus accumulation, Carbon-sequestration and ultimately soil fertility improvement (De Vries et al. 2013, Nair et al. 2010, Schubert 2017, Tebrügge and Düring 1999).

Intensive land use combined with low inputs of organic compounds and chemical treatments over several years reduces the diversity and abundance of soil biota and may lead to the necessity of revitalizing the soil before planting a food forest (De Vries et al. 2013). Soil additives like effective microorganisms (EM), which are a mixed culture of beneficial and naturally occurring microorganisms, applied in combination with organic compounds might enhance the process of revitalizing degraded soil, if the amount and application rate is sufficiently high (Joshi et al. 2019). However, there are contradictory results regarding the effect and working mechanisms of EM (Mayer et al. 2010, Olle and Williams 2013). This is primarily due to the complex processes and influencing factors within the soil food web, making it difficult to study.

In areas with little precipitation and sandy soils it might be helpful to apply other additives besides organic matter to enhance the water holding capacity and physical properties of the soil. The application of soil additives like bentonite, an absorbent swelling clay, or biochar improves the hydraulic properties and structure of sandy soils because, in contrast to compost, they remain in the soil for a longer period and resist biodegradation (Alghamdi et al. 2018).

2.3.4 Succession and disturbance management

As the structure of mature food forests mimics natural forests, it is important to study the development of a natural forest in order to transfer processes and mechanisms to the development of a food forest. The chronology of natural development is called ecological succession and describes the recovery process of an ecosystem following natural or anthropogenic disturbance. Primary succession occurs after extreme disturbances, such as landslides or volcanic eruption, and is initiated by lichens, algae and bacteria. Secondary succession occurs after moderate disturbances, such as fire, floods or storm, which leave an intact soil that can already be colonized by higher plant species, either through propagules present in the soil or through disperses from surrounding areas (Dalling 2008, Jacke and Toensmeier 2005).

In the last century a variety of different theories and ideas have emerged to explain the process of natural succession, but until today none of them are universally accepted (Clements 1916, Connell and Slatyer 1977, Egler 1954, Franklin et al. 2000, Gleason 1927, McIntosh 1999, Pickett et al. 1987, Tilman 1985). Those theories should be seen as non-mutually exclusive and often reproduce overlapping ideas and approaches or use different terms for the same phenomena (Pulsford et al. 2016). They can often be applied simultaneously or situation-dependent, as natural succession pathways are always dependent on the prevailing soil and climate conditions as well as the type and degree of the disturbance (Bormann and Likens 1994, Pulsford et al. 2016). Due to this complexity, researchers attempt to adapt and improve already existing theories rather than coming up with new explanations altogether.

The theory of Clements (1916), which shaped the view on succession in the 20th century, describes natural succession of vegetation as a linear process that starts with pioneer species on the bare soil and develops over different seral stages towards a climax vegetation that is mainly influenced by soil type, climate and possibly by human interference (Bormann and Likens 1994). Today it is widely accepted that natural succession is a complex dynamic process that can even run inversely for a short period, rather than a predictable or linear development (McIntosh 1999, Wilson 2011). The emerging climax community should also not be defined as a steady state, but more as a dynamic system that is continuously influenced by small disturbances (Gleason 1927, Malézieux 2012).

A highly debated topic is the colonization, the development, and the functions of pioneer species within successional pathways (Connell and Slatyer 1977, Egler 1954, Gleason 1927, Grime 1979, Tilman 1985). Pioneer species of secondary succession are usually able to quickly transform available nutrients from the soil into biomass and are therefore fast growing, but typically have a shorter lifespan and higher rates of decomposition and nutrient release than non-pioneer species (Covington 1981, Dalling 2008, Melillo et al. 1982). Figure 3 shows the natural colonization of a food forest by the pioneer species *Cytisus scoparius*, which derived via seeds from surrounding plants.

Figure 3 Natural colonization of the pioneer species *Cytisus scoparius* (in yellow blossom) on former arable land. Left image from summer 2020 before food forest planting. Right image from spring 2022 (own image)

According to Connell and Slatyer (1977) and Pulsford et al. (2016), three major theories can be summarized to describe the mechanisms of pioneer species:

Facilitation theory – Only pioneer species can colonize the area successfully after disturbance. The pioneer species influence the soil conditions, making it unfavorable for themselves, but suitable for the following seral stage (Connell and Slatyer 1977, Pulsford et al. 2016). During the succession, each stage produces the physical environment required by the following stage (Hart 1980).

Tolerance theory – Any species can colonize the area after disturbance. The pioneer species require many resources (nutrients, water and light) and will in the following be outcompeted by species which are more tolerant to lower resource levels (Connell and Slatyer 1977, Tilman 1985). The first species to leave the system are the least tolerant to limited resources (Gleason 1917, 1927). Intermediate disruptions during the succession can delay competitive exclusion and permit coexistence of species from different seral stages (Connell 1978, Grime 1973).

Inhibition theory – Any species can colonize the area after disturbance. Pioneer species inhibit the establishment and development of following species until they die or get damaged (Connell and Slatyer 1977).

These natural processes must be considered and can be utilized when creating a productive agroecosystem that incorporates natural succession. As potential negative effects of pioneer species on the following species only occur during the succession process of natural regeneration, those effects could be eliminated or converted into positive effects when managing the succession process of agroecosystems. Management techniques include intermediate disturbances of the system through pruning or cutting down entire pioneer species before negative effects on following species can occur. Appropriate human-made disturbances can accelerate the whole succession process, as they enhance nutrient fluxes and soil fertility (Abrams and Scott 1989, Connell 1978, Götsch 1995, Kumar and Nair 2006, Swanson et al. 2011, Vitousek et al. 1989). Various research shows, that through intermediate disturbances, several stages of succession can coexist within a small area, which enhances the biodiversity and consequently the productivity and stability of ecosystems (Denslow 1980, Eisenhauer et al. 2017, Gough et al. 2021, Lindenmayer 2009, van der Maarel 1993).

Incorporated pioneer species in a food forest can be managed as functional species, which enhance soil fertility and niche exploitation during the succession process (Corenblit et al. 2018). With their fast growth they initially provide an evaporation protection by shading surrounding soil and plants in summer (Wilson and Lovell 2016). The selection of pioneer species should contain a variety of nitrogen fixing shrubs and trees, such as *Alder*, *Elaeagnus* or *Robinia*, as they further import nutrients into the system.

When starting a food forest from bare soil, arable land or grassland, pioneer species also initiate a shift in soil microbial communities (Corenblit et al. 2018, Susyan et al. 2011). Succession influences soil microbes and is vice versa influenced by soil microbes. Fungi are assumed to be dominant in natural ecosystems and bacteria in intensively managed systems (Bardgett and Van Der Putten 2014, Boer et al. 2005, De Vries et al. 2013). Jiang et al. (2021) measured an increase of the relative abundance of ectomycorrhizal fungi during boreal ecosystem succession, while the abundance of bacterial functional groups remained unaffected. As nutrients temporarily deplete during the beginning of secondary succession, it is assumed, that association between ectomycorrhizal fungi and plants become more important, which results in shifts of active plant-associated communities from bacterial-dominated to fungal-dominated communities (Hannula et al. 2017, Holtkamp et al. 2008, Kardol et al. 2006). Another assumption is, that because fungi are known to dominate the decomposition of lignin containing substances, they appear more frequently as the succession of food forests develop and increasing amounts of woody material, derived through pruning and cutting of pioneer species, cover the ground (Bugg et al. 2011). When implementing food forests, the application of thick layers of wood chips and the integration of pioneer species therefore accelerates the development of fungi-dominated forest soil condition.

3 Material and methods

3.1 Research Design

Since there is little knowledge about food forests in Europe, a qualitative research approach was applied to explore the field and formulate ideas for implementation and further research. In qualitative research, a combination of different methodological techniques is used to ensure the collection of large amounts of information from multiple sources, which then helps to reduce bias and to enhance data credibility (Eisenhardt 1989, Marshall and Rossman 2014, Miles and Huberman 1994).

To approach the research objectives, semi-structured interviews with food foresters, expert interviews, as well as site visits were conducted. The interviews with the food foresters and site visits aimed to assess the main services, management practices and sustainability of each food forest. Subsequently, expert surveys were conducted with the focus on the broad potential of food forests in the European food system. The selection of experts was based on the assumption, that long-term practitioners can play an important role in collecting research relevant knowledge through their own field experience (Shreck et al. 2006, Velten et al. 2015).

In total 30 food forests from 11 European countries were investigated in this study, whereas 19 interviews took place during site visits. Twenty-two private and eight community food forests from the following countries were included: Germany, Netherlands, France, Finland, Sweden, Norway, Italy, Ukraine, Switzerland, Austria and the UK (Fig. 4)

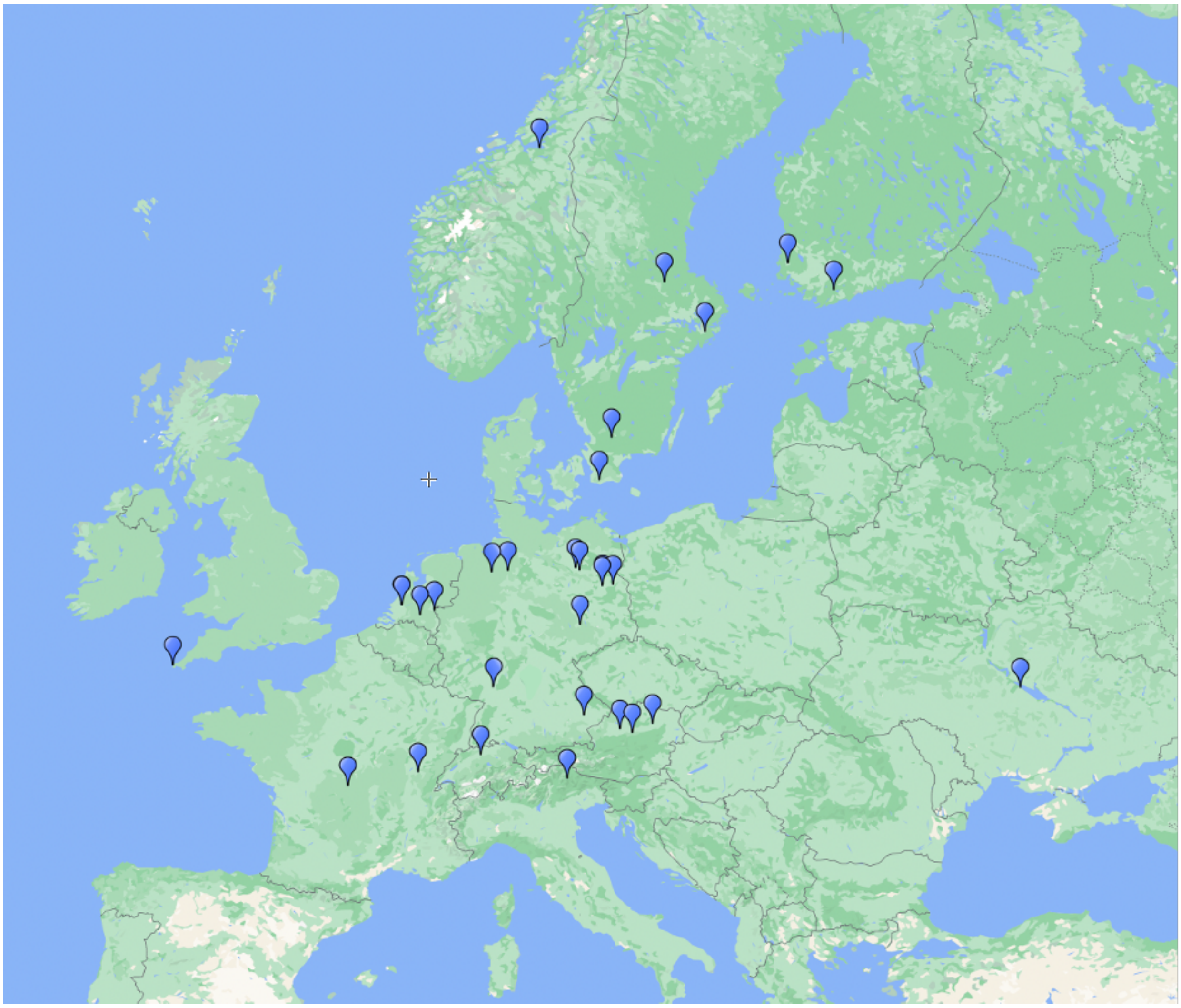


Figure 4 Geographical distribution of investigated food forests (n=30) (created with scribblemaps)

3.2 Data collection

Data collection from the 30 food forests took place between February 2022 and September 2022. Interviews were carried out in-person during site visits or through video call. The duration of an interview was usually between one and two hours and a site visit between a few hours and one day. The questions were framed in an open conversation and often merged into a discussion about specific design and maintenance techniques, site-specific problems, or the general potential of food forests in Europe. With the consent of the interviewee, each interview was recorded and later analyzed. To protect the interviewees' privacy, sensitive data was anonymized, and only specific content was cited in the result presentation with the consent of the respective interviewee.

Selection of interview partners

To identify possible food forests and experts for the research, a web-based search in English (“food forest“, “forest garden“) and German (“Waldgarten“) was conducted. Beyond the web search, first contacts in the field of food forests were made 4 years before starting with this research through several visits and conversations. In the course of this study, food forests and experts were then identified through purposive snowball sampling, starting with the help of a few individual contacts and data banks like the “The Agroforestry and Forest Garden Network“ or different permaculture associations from European countries (ART 2023).

In order to enhance project comparability, the research area was limited to the Oceanic and Continental climates of Europe, excluding the Mediterranean Climate, which offers a decisively different variety of available plants (Peel et al. 2007). According to the Köppen climate classification of Europe the zones Cfb, Cfc and Dfb, Dfc are included (Beck et al. 2018). To provide a holistic insight into the topic, food forests with different ages, main services and management practices were selected (Table 2).

The selection criteria for private food forests were, that their main services go beyond self-sufficiency and that an income is currently generated through the food forest or is planned to be generated in the future. Two interviews were conducted and subsequently excluded from the study, because selection criteria were not fulfilled. The willingness to participate in the research program and the accessibility of the site also determined the selection of the studied food forests and whether they were visited or not.

Interview structure

The semi-structured interview with one or more persons involved in each food forest was conducted with the goal to assess the main services, management practices and sustainability of the food forest. The interview was segmented in three parts including the social-cultural, ecological, and economical state of the food forest. The questionnaire for community food forests was adapted to include further questions on the social part of the initiative (Appendix A). Similar to Albrecht and Wiek (2021a), two main services were identified by standardizing the most common activities and objectives of each food forest. Management practices are closely linked to the sustainability of food forests and were observed during site visits and further enquired through interview questions, which were included in the ecological section of the interview.

Following the questions about the food forests, an additional part of the interview was dedicated to the identification of certain factors that influence the contribution of food forests to the food system in Europe. The main focus was on how food forests can improve their contribution towards the food supply. Those expert questions were only addressed to experienced food foresters (In-topic for at least 4 years), which included 20 of the 30 interviewed food foresters.

Sustainability assessment

A set of sustainability criteria, modified from Albrecht and Wiek (2021a), and corresponding interview questions were established to assess the sustainability of each food forest with regard to the SDGs (Table 1). The interview questions were identified through monitoring frameworks for food forest and forest sustainability (Elvers et al. 2019, Huijssoon et al. 2017, Park and Higgs 2018, Wiersum 2004, Wright and Alward 2002), sustainable development assessments (Chaudhary et al. 2018, Sachs 2015) and expert interviews, as well as test interviews with food foresters.

Table 1 Sustainability criteria of food forests (modified from Albrecht and Wiek, 2021a)

Criteria		Definition
Social-Cultural Criteria	Safe, purposeful & Mutually beneficial employment	• Protective working gear, Diverse working activities, Respectful working engagement, Satisfaction from work, Social justice, Fair wages, Gender equality, Participation in decision-making, Integrity in the workplace • Organized events and meetings for employees besides working
	Education & Training	• Capacity building through sharing of food forest related knowledge and skills • Awareness-raising and capacity building on climate change mitigation • Participation in research and science

	Contribution to community well-being	• Production of advantageous products and services for the community (Healthy food; regional products; jobs; educational and recreational activities; retreat area…)
Environmental Criteria	Water conservation & Soil enhancement	• Techniques to enhance water conservation (Rainwater harvesting; water retention areas…) • Techniques to enhance soil fertility (Ground cover; mulching; use of pioneer species, Terra Preta, EM, compost…)
	High biodiversity	• Species and genetic richness of flora and fauna, Wildlife-habitat (Undisturbed areas; connection to green corridors…) • Creation of heterogenous landscapes with habitats for antagonist species
	Local climate regulation	• Creation of local microclimate depending on local climate conditions (Cool climate through dense, multi-layered design with high canopy and ground cover; Warm climate through sun traps, stonewalls, swales…)
Economic Criteria	Economic viability	• Economically self-sufficient (Outputs exceed inputs and costs), Sustaining livelihood of staff (At least one part time position) • Long-term appropriate use of resources (Human and material)
	Progress tracking & Monitoring	• Enhancing progresses and production through documentation and adaptions (Site plans, tracking yields, annual reports…)
	Support funding & Land ownership	• Institutional or cooperative participation in funding and ownership to ensure durability of project • Long-term land ownership

3.3 Data analysis

To present an overview of the investigation, a standardized profile for each food forest was created, including information about the main services, location, size and age (Table 2). These basic information as well as observed structures and management practices of food forests are presented descriptively.

Regarding the interview, the answers to each question were transcribed in form of key notes and extended by own observations during site visits. Additionally, some statements were transcribed word-for-word to allow citations in the result presentation. After the transcription process, data analysis was performed by applying the qualitative content analysis according to Kuckartz (2014), which supports a combination of concept-driven (deductive) and data-driven (inductive) coding allowing the development of main categories before starting the coding process (Kuckartz 2014, Schreier 2012).

Sustainability assessment

For the sustainability assessment an evaluative quality text analyses of the interviews was conducted (Kuckartz 2014). In this case the criteria catalogue (Table 1) represented the developed categories and codes. These categories were mainly identified from Albrecht and Wiek (2021a) and adjusted with the help of experts and test interviews with food foresters prior data collection. The catalogue was then applied deductively to the data set. While the terms social-cultural, environmental and economic sustainability presented the main categories, the corresponding criteria, such as “education and training“, “high biodiversity“ or “economic viability“ summed up the codes (Table 1). The interviews were analyzed according to the definitions of the respective code.

The assessment for each criterion could either be 0 (not met), 1 (somehow met) or 2 (fully met), depending on the overlapping content between the interview answers and the definition of the criterion. If there was no consensus in a wider context between interview answers and criterion definition, the received score was 0. If at least one point from the criterion definition was mentioned in the right context, the received score was 1 and if every point from the criterion definition was mentioned in the interview answers, the received score was 2. Individual scores were then merged for all food forests to present the average result for each sustainability criterion. Thereby it was ensured, that the results from the sustainability assessment were anonymized each food forest.

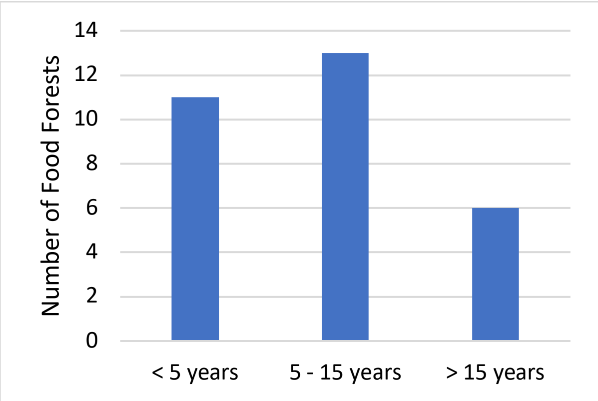
Expert interview

The part of the interview dedicated to the expert questions was then analyzed through inductive and deductive coding applying the thematic quality text analysis by Kuckartz (2014). Due to low scientific groundwork in the field of food forests, only the main categories were entirely applied to the dataset deductively, while most of the codes derived from the analyzed data set inductively. The coding guideline was therefore constantly adjusted during the data analysis (Appendix B)

4 Results

4.1 Age, size and main services

As shown in Figure 5, most investigated food forests were less than 15 years old and below 5 ha in size. The average age of the food forests was 10.7 years and the average size 1.8 ha.



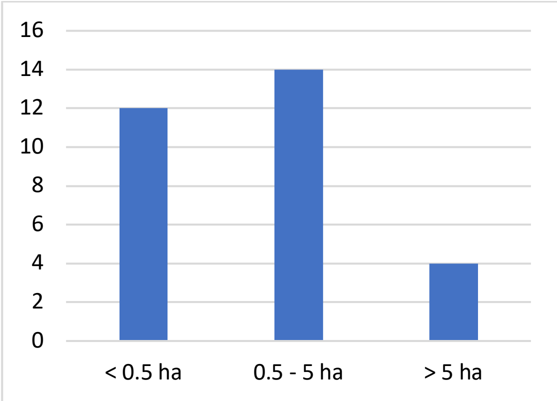


Figure 5 Left: Age (in years) of investigated food forests (n=30). Right: Size (in ha) of investigated food forests (n=30).

Figure 6 shows the allocation of the indicated main services over all investigated food forests (Table 2). The largest proportion of food forests (37%) serve at least partly as educational platforms with the focus on teaching food forest design and management practices, presenting new food choices and diets, as well as raising awareness of ecological processes and climate change. Educational endeavors, such as food forest tours, events, and courses, can also serve as a secondary income tool. An additional income through book sales and holding lectures can also be linked with the food forest, as the presented knowledge is often based on the experiences and learnings from said food forests.

A direct income is generated by 19% of the investigated food forests either through the marketing of primary or processed products, or by using propagation material from the food forest. Marketing strategies include cooperation with restaurants, local food sellers, food cooperatives or community shared agricultures (CSA). Other strategies are online and direct sales, sometimes mentioned as “event-shopping“ during courses, events and tours. One investigated food forest serves as a mother garden for a tree nursery business and another two generate an income by selling processed products, such as juices, dried herbs or marmalades, from the food forest.

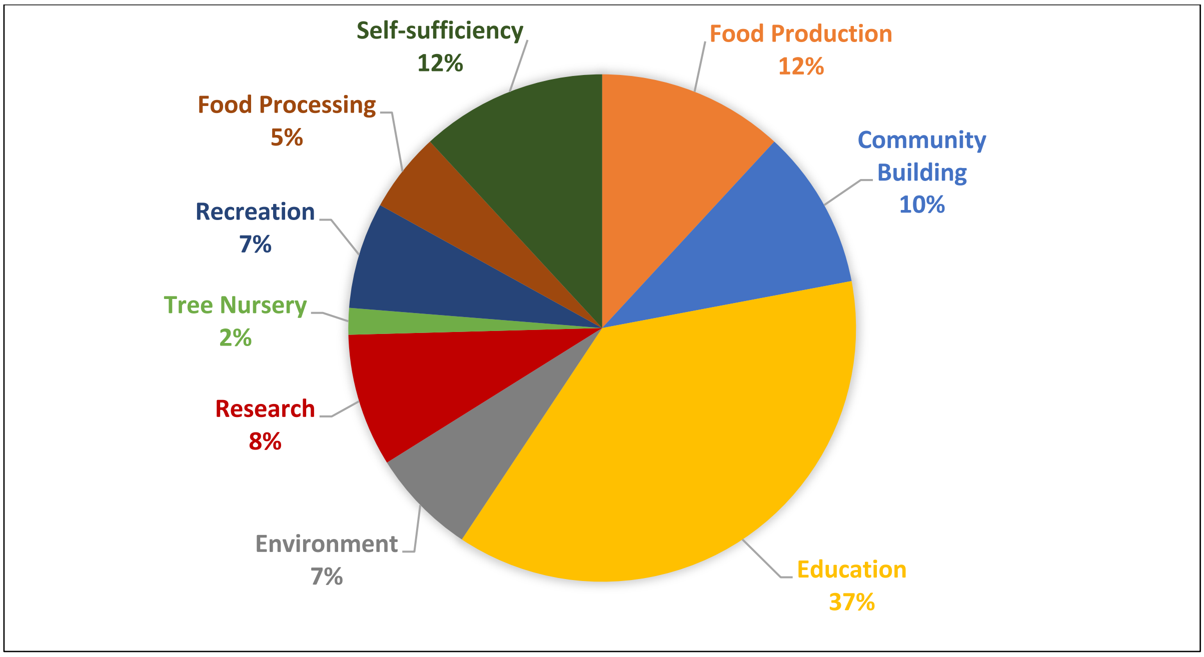


Figure 6 Allocation of main services (two per food forest) (n=30)

Even though self-sufficiency (Production for own consumption), recreational purposes and environmental benefits are inherent with most of the food forests, for 26% of the food forests those are especially important main services. Community building occurs as a main service exclusively in community food forests with a good connection to urban infrastructure. Eight percent of the food forests mainly focus on research either on a private scale or in cooperation with different institutions, such as universities.

Table 2 Basic information (Name, Location, Main services, Size, Year) of investigated food forests (n=30)

Name	Location	Main services	Size	Year
Allmende Waldgarten e.V. Verden	Germany/ 27283 Verden	Research/ Education	7 ha	1998
Allmende Waldgarten Edingen-Neckarhausen e.V.	Germany/ 68535 Edingen-Neckarhausen	Education/ Community building	0.2 ha	2021
ATMOSVERT Pépinière permacole	France/ 23270 Saint-Dizier-les-Domaines	Tree nursery/ Education	1.2 ha	2015
Café Botanico	Germany/ 12043 Berlin	Food processing/ Education	0.1 ha	2011
Den Food Bosch	Netherlands/Schuilenburg, 5271 VR Sint-Michielsgestel	Primary production of food/ Research	1 ha	2017
Essgarten	Germany/ 27243 Winkelsett	Education/ Recreation	2.4 ha	1990
Food Forest Alta Badia	Italy/ 39033 Corvara in Badia BZ	Environment/ Education	12 ha, edibles just on path	2021
Forest garden by Stephen Barstow “The Edimentals“	Norway/ 7563 Malvik	Self-sufficiency/ Education	0.23 ha	1984
Food Forest by Tatyana Diner	Ukraine/ Close to Tscherkassy (Черкаси)	Food processing/ Primary production of food	1 ha	2019
Forest garden “Grüner Engel“	Austria/ 3131 Getzersdorf	Food processing/ Education	0.3 ha	2002
Forest garden Bernhard Gruber (Österreichisches Waldgarten-Institut)	Austria/ 4501 Neuhofen an der Krems	Self-sufficiency/ Education	0.43 ha	1992
Forest Garden by Joel Rosenberg	Finland/ 23800 Laitila	Self-sufficiency/ Education	0.2 ha	2011

Forest Garden by Joscha Boner	Switzerland/ 4813 Uerkheim	Recreation/ Self-sufficiency	0.2 ha	2019
Forest Garden Gammelgård	Sweden/ 343 97 Älmhult	Self-sufficiency/ Education	0.1 ha	2017
Kylänpään Kotitila Forest Garden	Finland/ 09120 Karjalohja	Education/ Environment	1 ha	2019
La Forêt Gourmande	France	Self-sufficiency/ Education	2.5 ha	2010
Mienbacher Waldgarten/ Selbstversorger Akademie	Germany/ 94419 Mienbach	Education/Self-sufficiency	1.5 ha	2010
Peace of Land (Permakulturakademie e.V.)	Germany/ 10407 Berlin	Education/ Community building	0.3 ha	2016
Project WASYS Kyritz by STATTwerke e.v.	Germany/ 16866 Kyritz	Research/ Education	5.4 ha	2021
Putt Myra Forest Garden	Sweden/ 770 71 Stjärnsund	Research/ Education	1.5 ha	2011
Rågdalens Skogsträdgård	Sweden/ Stuvsta, Huddin	Primary production of food/ Community building	0.2 ha	2009
Rydeholm Skogsträdgård	Sweden/ 231 70 Anderslöv	Environment/ Recreation	Old: 1.2 ha New: 0.5 ha	Labeled in 2010
SoLaWi Waldgarten	Germany/ 16866 Gumtow	Primary production of food/ Research	5.2 ha	Old: 2006 New: 2020
Voedselbos Ketelbroek	Netherlands/ 6562 LR Groesbeek	Primary production of food/ Education	2 ha	2009
Voedselbos Kralingen	Netherlands/ 3061 PK Rotterdam	Community building/ Education	0.19 ha	2013
Voedselbos Overtuin	Netherlands/ 3062 NX Rotterdam	Education/ Primary production of food	1.46 ha	2018
Wald & Wiese Leipzig	Germany/ 04328 Leipzig	Education/ Recreation	0.9 ha	2016
Waldgarten-Allmende Allhartsberg	Austria/ 3365 Allhartsberg	Community building/ Education	App. 0.2 ha	2013

Waldgartenpilot Rehfelde	Germany/ 15345 Rehfelde	Primary production of food/ Education	2.7 ha	2021
Worlds End Forest Garden	United Kingdom/ Penzance TR19 7HS	Community Building/ Environment	0.92 ha	2018

4.2 Structures

Food forests can be distinguished by different structures, which are normally influenced by the specific site characteristics and the ecological or social perspective of the designer. Six investigated food forests are designed in a linear structure, with either straight (Fig. 7A), curved (Fig. 7B) or keyline based rows of plants. In most cases, tree rows are oriented in North-South direction, sometimes in East-West direction. 19 of the 30 investigated food forests can be characterized as wild or "romantically" designed food forests (Fig. 7C). The distribution of plants might follow certain patterns, but appears more or less random to observers and resembles the structure of a natural forest.

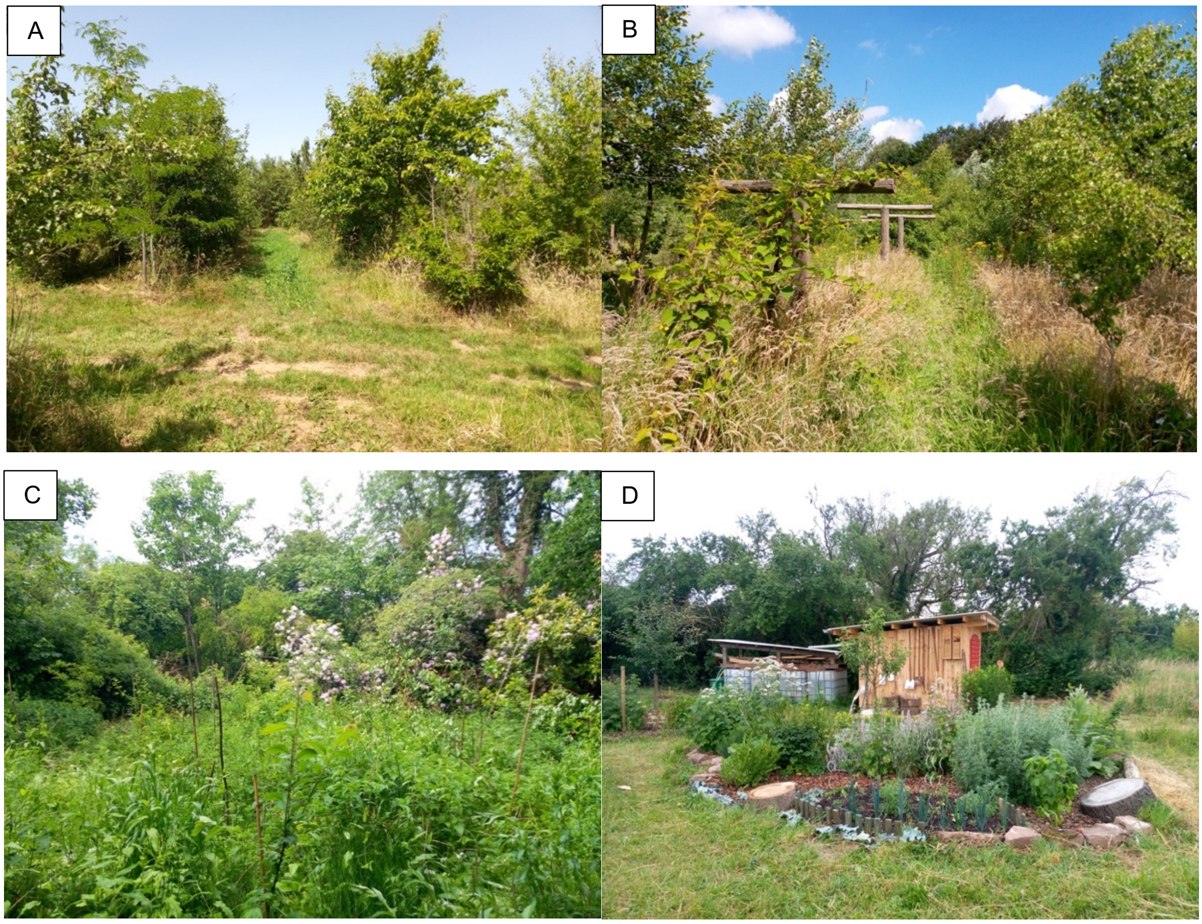


Figure 7 A: Linear tree rows at "ATMOSVERT Pépinière permacole", B: Half circled tree rows in "Den Food Bosch"; C: Wild arrangement in "Voedselbos De Overtuin"; D: Circular plant guilds in "Allmende Waldgarten Edingen-Neckarhausen e.V." (Own image)

Three food forests are characterized by a combination of linear and wild arranged plants. Another two community food forests are organized in circular plant guilds, presenting an arrangement of the different layers of a food forest in each plant guild (Fig. 7D). Independent of the structure, it was observed, that tree height often increases towards the north. The exemplary structures of the food forests in figure 7 are schematically illustrated from an aerial perspective in figure 8.

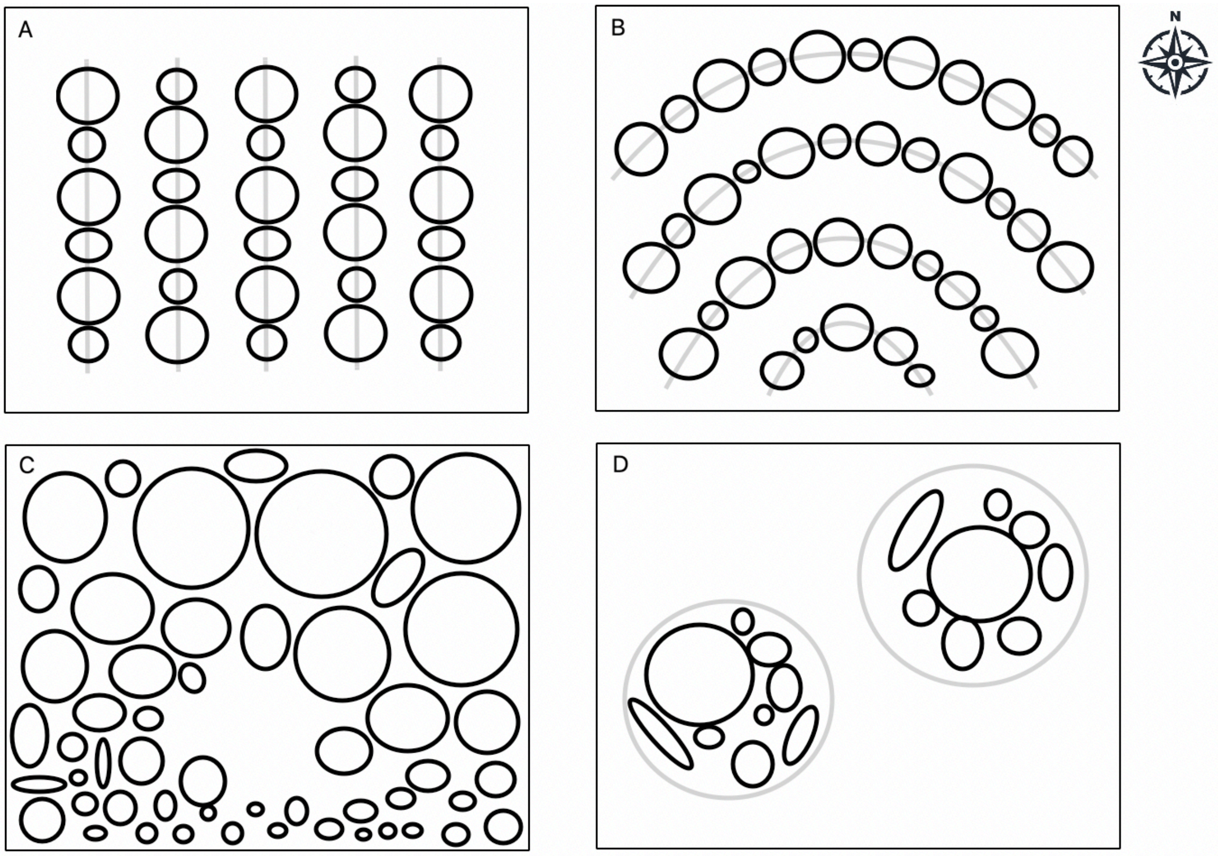


Figure 8 A: Food forest with linear tree rows oriented in North-South direction; B: Food forest with half circled tree rows oriented to the South; C: Wild food forest with increasing tree height towards North; D: Food forest in circular plant guilds (Own illustration)

4.3 Management practices

The most conducted management practices or time-intensive working activities in food forests were found to be dependent on the age of the food forest and the season of the year. In young food forests (< 5 years) the most time-intensive working activities are mulching, weeding and watering during spring and summer as well as planting in winter and autumn. Year-round tasks are site clearing, observation, social work and marketing. In older food forests (> 5 years) weeding, watering and planting tasks play a subordinated role while fruit tree pruning, chop and drop practices for pioneer species as well as harvesting and processing are the most time-intensive working activities. Social work and marketing remain a year-round task in older food forests.

Fruit tree pruning

Especially in the Netherlands, but also in other food forests, food foresters do not prune fruit trees at all, explaining it with the fact that no scientific evidence shows the positive impact of pruning. An equal share of food foresters performs fruit tree pruning without having participated in certified training in advance. In this case, pruning is performed “according to the feelings“ of the manager. The minority of food foresters perform pruning based on prior participation in certified training programs or on long-term experience.

Pest and disease management

Common pests in food forests are voles, deer, field mice and rabbits, while problems with birds and snails only occurred in four food forests. Humans with dogs were further mentioned as a “pest“ in two community food forests, as they damage plants and urinate on harvest. Problems with birds, which pick fruits prior harvest, mostly occur within the first years, when the surrounding landscape does not offer enough food alternatives. Management methods against animal pests are vole baskets, protecting nets, single protective tree covers or the implementation of a fence around the food forest. Voles and field mice present a major problem in young food forests, because protective baskets can degrade very fast, depending on the soil type. In matured food forests with a well-rooted soil, tree losses through voles tend to decrease. Some food foresters therefore use the strategy of dense tree planting, including *Salix* and *Betula* cultivars, which seem to be avoided by voles, from the beginning, as a natural protection against voles. Another method used is the integration of plants from the *Euphorbiaceae* family as well as injecting *Narcissus* and *Allium* bulbs into the plant hole during the planting process.

Other pests and diseases identified in the food forests are the following:

- Apple scab caused by the fungus *Venturia inaequalis*
- Brown rot blossom blight disease caused by the fungus *Monilinia laxa*
- Peach and apricot leaf curl caused by the fungus *Taphrina deformans*
- Chestnut ink disease caused by the oomycete *Phytophthora cambivora*
- Light brown apple moth (*Epiphyas postvittana*)

- Walnut husk fly (*Rhagoletis completa*)
- Different varieties of canker, collar rot and fire blight

The most common method used in the investigated food forests is preventive pest and disease management. This includes the integration of antagonist host plants and supportive plants as well as the adapted species and cultivar selection according to the site and soil conditions.

On the occurrence of diseases, the majority of food foresters do not carry out further management practices. This was explained through the diverse cultivation of different plant species, making single infected trees not a major treat to the overall harvest. Many food foresters also explained that pests and diseases function as regulators in the beginning and can be neglected, as the food forest evolves to a more balanced ecosystem over time. However, as the climate in food forests gets moister during the succession, specific fungi diseases tend to occur more often in dense, matured food forests. Some food foresters therefore use specific treatments depending on the disease. Glucosinolate containing plants are planted under fungi susceptive fruit trees, such as peaches, or glucosinolate and other herbal mixtures are applied directly on the affected area. Another common technique is the removal of infected plant parts through pruning.

4.4 Sustainability assessment

The sustainability assessment shows that food forests perform well on social-cultural and environmental criteria by benefitting the local community through healthy food and education or by conserving and restoring biodiversity and soil fertility. On the other hand, food forests tend to be unsustainable in terms of economic viability, often showing insufficient income, missing financial support and uncertain land ownership. In the following, each criterion is described more precisely and the received score out of available 60 points in the sustainability assessment is presented in the respective headline (Figure 9).

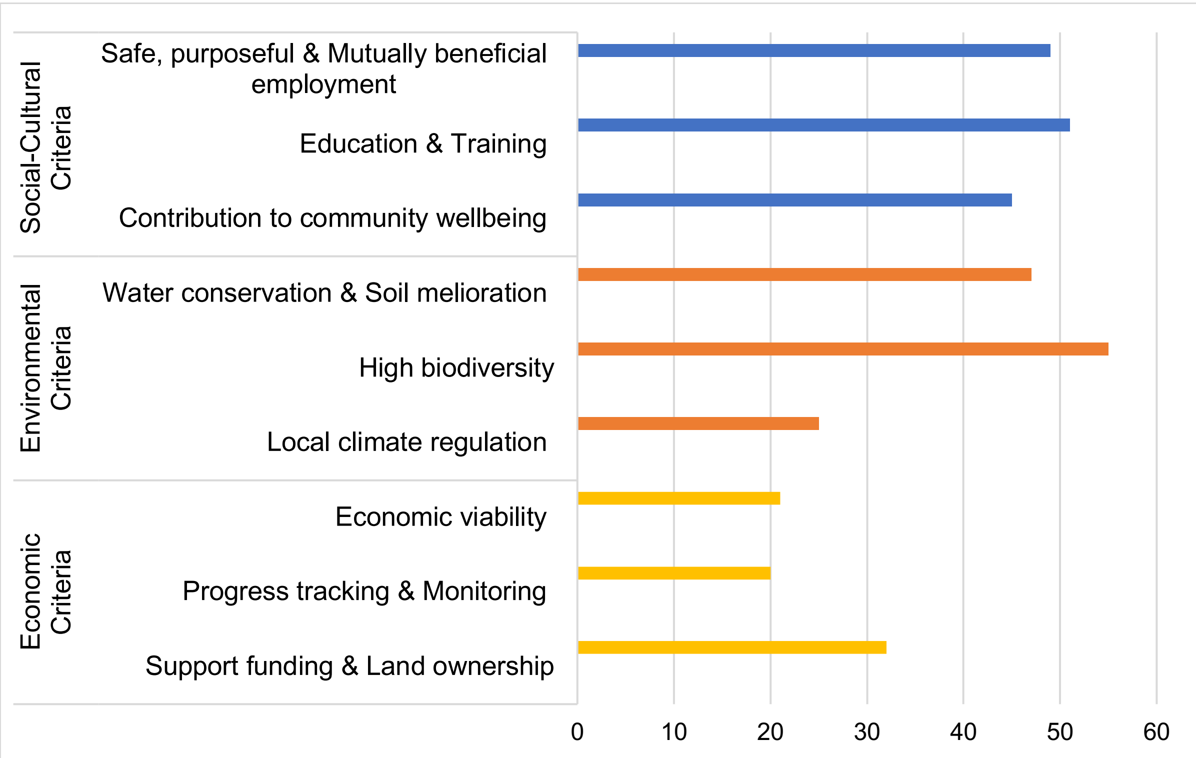


Figure 9 Average score in the sustainability assessment for the investigated food forests (n=30) by social-cultural, environmental, and economic criteria

Social-Cultural Criteria A - Safe, purposeful & mutually beneficial employment (49/60)

Nearly all investigated food forests (29 of 30) offer purposeful and fulfilling working activities for owners and employees. Working in the food forests is perceived as a method to restore a connection to nature as well as a lifestyle rather than work. Strong positive feelings are related to restoring nature and caring about plants and animals.

“Let's give nature back a piece of land.“
(Reinhard Engelhart, founder of waldgarten.global, 2022)

With developing canopy, the shading effect and the transpiration cooling of trees forms a more pleasant working environment in food forests compared to the open field during hot summers. However, an entrepreneur from the “ALTA BADIA Food Forest“ in Italy mentioned that any forest remains a dangerous working space and protective working gear is mandatory.

Social-Cultural Criteria B – Education and training (51/60)
All investigated food forests (30 of 30) offer educational activities or share knowledge about food production, ecology or climate change related topics.

P. Weiss from “Putt Myra Food Forest“ in Sweden for example offers a college course about food forests and shares the food forest with students to experiment with their own designs. H. Zech from “Mienbacher Waldgarten“ in Mienbach, Germany organizes permaculture design courses and provides food education to the neighborhood. R. Teufl from “Waldgarten Allmende Allhartsberg“ in Allhartsberg, Austria offers tours about wild edible herbs and other plants. In many community food forests knowledge sharing takes place during work activities or group meetings.

Social-Cultural Criteria C – Contribution to community well-being (45/60)
Nearly all investigated food forests (28 of 30) contribute to the local community well-being either through production of food, educational services or recreational values. The goal of the “gerilla-network Tillväxt", initiator of the community food forest “Rågdalens Skogsträdgårdan“, is to change the way in which Swedish people view common spaces, unused land and parks. Their slogan is: "Free, organic, locally produced food for everybody to harvest".

“Food forests will (partly) change the food supply to a local affair […] *by involving the local community in management and maintenance. The local community will regain a connection with the origin of their food in contrary to the anonymized global food supply. This will change the way people take care for the land that provides healthy food.“*

(Maurice Ramaker, manager of “Den Food Bosch“, 2022)

Figure 10 Demonstration food forest “Gammelgård” in Sweden (Image from S. Meyer)

C. and S. Meyers (“Forest Garden Gammelgård“ in Sweden, Fig. 10) goal is to show how it is possible to create and manage a food forest while also holding a full-time job and thereby increase own self-sufficiency. They helped designing and implementing eight new food forests in the local community in the last three years.

Two investigated food forests did not show any contribution to community well-being, due to their remote location and preference of the owner.

Environmental Criteria D – Water conservation and soil enhancement (47/60)

Soil and water conservation strategies were practiced and mostly resembled each other throughout all investigated food forests (30 of 30). Common soil enhancement strategies in food forests include chop and drop and mulching practices as well as the use of organic material such as compost or manure. However, some food foresters refer, that the effect of early organic additives on long-term tree development is still unclear and might even be contra productive.

“Compost might not be needed for a tree. If they get phosphorus for free, they are not cooperating with mycorrhizal fungi anymore, which is the most important thing happening for a tree alive for the next centuries. Might be our impatience to want to see them grow fast in the first 5 years, but this is nothing in the long run.“
(Wouter van Eck, manager of “Voesdselbos Ketelbroek“, 2022)

Organic plastic sheet mulch is also used in some food forest to suppress the growth of surrounding weeds in the juvenile stage. A specific strategy, which is used by the “Project WASYS Kyritz“ by STATTwerke e.v., is the application of soil additives, such as biochar, bentonite or other clay minerals. S. Lehman explained, that due to the sandy soil conditions at their site in Brandenburg, Germany, the development of a decent soil structure is required before the application of organic compounds shows to be useful.

Water conservation is achieved through rainwater collection and implementation of water retention areas such as swales or ponds. Both, J. Boner in Switzerland and T. Diner in the Ukraine, created swales filled with organic material to enhance water holding capacity and fertility of the soil. Before planting at the “Worlds End Forest Garden“ in Penzance, UK, terraces were built to reduce water run-off.

Environmental Criteria E – High biodiversity (55/60)
The investigated food forests received their highest sustainability score of biodiversity conservation or restoration (55 of 60). Thus, nearly all food forests (29 of 30) showed to influence surrounding biodiversity positively through conducted management practices, diverse plant species, undisturbed areas for wildlife or creation of heterogeneous habitats. Often, food foresters noticed changes in the surrounding fauna within the first years. The 0.23 ha food forest of S. Bartow in Malvik, Norway for example counts more than 8000 plant species or cultivars as well as more than 200 different moth species. The “Essgarten“ in Winkelstett, Germany habours more than 1200 different plant species on 2.5 ha.

The biodiversity of some food forests was limited due to their site size or missing connections to green corridors. Nonetheless, the plant biodiversity exceeds that of surrounding areas in nearly all food forests, according to the practitioners.

Environmental Criteria F – Local climate regulation (25/60)

A local climate regulation was mostly achieved in older (>5 years) and large-scale (>0.5 ha) food forests (18 of 30). It was observed that the creation of a cool microclimate was achieved faster when planting pioneer species from the beginning, due to their fast growth. In most of the food forests, a general regulation towards a cooler climate is desired and only small areas are created as suntraps to increase the overall heterogeneity of the area. In far northern located food forests in Malvik, Norway and Stuvsta, Sweden for example the applied design strategies tend to achieve an overall increasement in temperature.

Economic Criteria G – Economic viability (21/60)

An income from food forest associated activities, such as the organization of presentations, courses or tours, product sales, book writing or help with implementation and design, was generated in 14 out of 30 food forests. However, the income generated from these activities was rather low and fluctuating. It did therefore not provide a livelihood without external support. An independent economic viability was found in 7 out of 30 investigated food forests, whereas a sufficient income exclusively generated to food forest associated activities was mentioned in only three food forests. T. Diner from the Ukraine for example can fully maintain her livelihood by selling processed products from the food forest, which she markets as healthy alternatives to conventional medicine. In the other four with independent economic viability, the income from the food forests presents one part of a larger business concept. At the “SoLaWi Waldgarten“, the parts for the CSA shares from the food forest currently constitute approximately 10%, while the other 90% stem from annual vegetables.

In the eight investigated community food forests no ambition for economic viability was reported.

Economic Criteria H – Progress tracking and monitoring (20/60)

In 18 of 30 food forests the development of the plantation is documented and the design as well as management strategies are being adapted to changes. A site plan is also available for most of the food forests, but is often not up-to-date in mature food forests. Full bookkeeping, such as yield tracking, changes in plant compositions on the site plan as well as annual reports, is carried out in two of the investigated food forests. Many food foresters explained, that due to missing time capacity and complexity of the system and its diverse harvest, sufficient progress tracking and monitoring proves to be difficult.

Economic Criteria I – Support funding & Land ownership (32/60)

Ten out of 30 food forests have to deal with uncertain long-term land ownership, due to temporary renting contracts and unsecure renting partners. Safe long-term land ownership is mostly achieved through privatization of property, but also when renting partners, such as communities or water authorities, share interests with the food forest initiative. Only few food forests are supported with external funding and are therefore often financed through the private income of the owner. However, some projects, such as “Waldgartenpilot Rehfelde“ in Rehfelde, Germany, obtain external support from companies or organizations. In this case the food forest obtained financial support for the land purchase and food forest implementation from the “Deutsche Postcode Lotterie“, because they are obligated to ecological compensatory measures. Many food forests also call for private donations and advertise “Participation days“ to finance and maintain the food forest.

4.5 Factors influencing the contribution to the food supply

Management challenges

Because of their complexity and diversity of plants, randomly arranged food forests can usually only be managed by well-experienced participants, often only by the owners themselves. Due to long training periods, which are required for new employees or volunteers, seasonal workers for labor peaks during harvest are rarely profitable and useful. Especially large, complex food forests are therefore difficult to manage, as they require manual labor and are not suitable for mechanized workflows.

A simplification of the system through a linearly structured plantation and a reduced species diversity in combination with the inclusion of certain cash crops, was found to enhance management processes. The linearly structured food forests “Grüner Engel“

and “ATMOSVERT Pépinière permacole“ experienced improvements in manual and mechanized workflows. However, the harvest of crops remains manual labor in structured food forests but could more easily be carried out by seasonal workers. Self-picking models, an approach where consumers gather the produce directly from the field themselves, could also represent an interesting harvesting strategy for food forests. These models, however, require a large catchment area and education for participants prior to harvesting. If the food forest is structured and crops with a similar harvest period are planted together in one row or in clusters, the required education for new participants is limited to the “pick-up” process instead of an explanation of the whole structure. New technologies for fruit harvest processes were also mentioned, to possibly simplify future management.

New plantings in young food forests are always limited by water availability and the capacity to supply water artificially. Depending on the location, plants must be watered for approximately one to four years after planting. Experts described the annually intensifying global water scarcity as a threat for present and future food forest planting and tree planting. Thus, a good water strategy before starting with the implementation of the food forest was identified as a determining factor for success in the first years. For Max de Corte from the “Coöperatie Ondergrond“ in Rotterdam this means: “First plant water, then plant trees.“ In terms of watering, F. Wesemann from the “SoLaWi Waldgarten“ experienced a synergy between vegetable production and tree growth. When the space between the tree rows is used for vegetable production in the first years, the trees also benefit from the vegetable irrigation. In this case, water sprinklers are required, and the water consumption is very high. This, however, is normal in any vegetable production system.

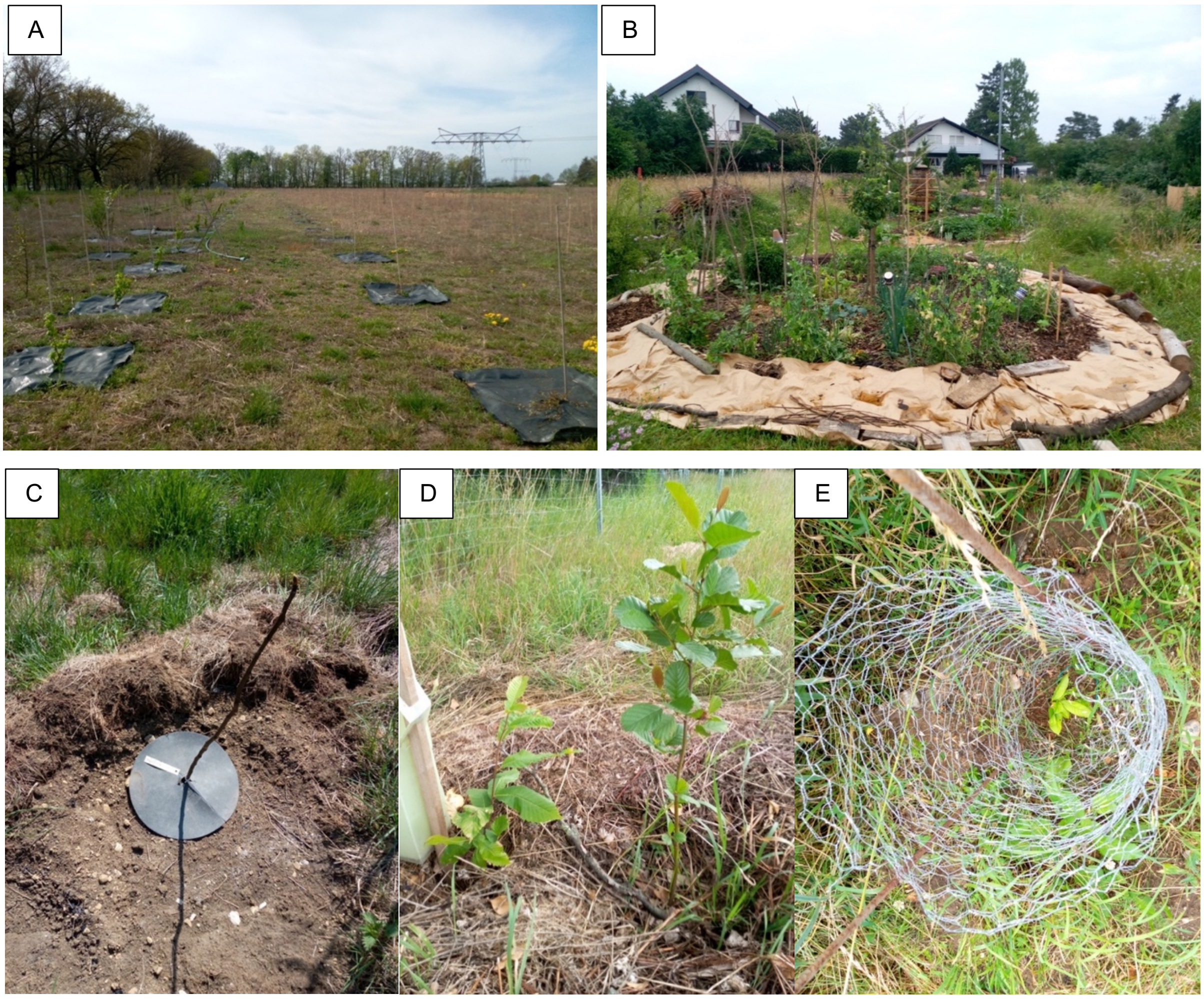


Figure 11 Different planting methods in food forests. A: Degradable plastic mulch; B: Wood chips and Paper; C: Rubber mat and tree slice for *ficus carica*; D: Straw mulch and pioneer species *alnus incana* for protecting *castanea sativa*; E: No mulch, diminished growth of *asimina triloba* (Own image)

Water concurrence with surrounding grass also diminishes tree growth in the first years and requires frequent weeding (Fig. 11E). Different mulching techniques are used to support early plant growth (Fig. 11A-D), as they can partly suppress the growth of surrounding grass. Degradable plastic sheets or thick layers of organic mulch are commonly used. Also the early incorporation of pioneer species was found to suppress the growth of grass by providing fast shade. Nevertheless, practitioners argued that a lot of manual labor is required for weeding in the first years, which again requires education prior the working process. It was also suggested that even if early concurrence with grass might reduce shoot growth of trees, it could also force them to create deeper root systems, better adapted to future climate conditions.

“*Especially when trees are young, they need neighbors for shelter, high humidity and reduced solar radiation. The young ones dislike exposure. They start extremely slow if they have too much space around*. [...] *Can be helpful to only plant pioneer species in the first winter, especially on open land.*“
(Wouter van Eck, manager of “Voesdselbos Ketelbroek“, 2022)

According to experts, the general use of pioneer species has a positive effect on the overall development of food forests. Some trees, such as *Quercus* or *Asimina*, prefer shade in the juvenile stage and can be densely planted together with pioneer species. On the other hand, dense planting was also observed to increase the amount of time that is required for maintenance when the food forest evolves. The required time for pruning and chop and drop practices is often dependent on the plant density of pioneer species.

Due to the early competition with grass, the establishment of an herbaceous layer is the most management intensive layer in a food forest. Experts on herbaceous plants therefore often recommend waiting with the implementation of the herbaceous layer until the food forest is further evolved.

“*Working with the time is important. After trees grow taller, the microclimate changes, increasingly shaded areas are emerging. Grasses and other species, that cause trouble when you want to establish a perennial herb layer, will decrease. You can wait until more suitable conditions arise and place everything in the right time*."
(Roland Teufl, founder of “Waldgarten-Allmende Allhartsberg“, 2022)

Harvest losses caused by pests and diseases can often be neglected in food forests due to the diverse range of harvestable products. However, late frosts and extreme weather conditions can significantly impact the harvest and the entire plantation. The vulnerability to late frost events depends on the location and climate conditions. It tends to decrease as the food forest develops a closed canopy and an own microclimate. While late frost events only affect specific harvest products, heavy hail events can destroy large amounts of the harvest and cause significant harm to individual plants.

Social Adoption

The social acceptance of new products from food forests and the integration of society into food forest projects determines the general adoption of food forests. Education about food forest benefits as well as the presentation of new products, plant species and applicable recipes through social-media or on TV can be one method to reach society. Experts furthermore mentioned that the aesthetic of the design strongly influences people's attitudes toward food forests. However, a broad social acceptance of food forests requires direct contact with new products and participation in food forest projects. Cities and communities can function as role models in this context and create suitable framework conditions for the social adoption of food forests by converting public spaces, like parks or schoolyards, into edible landscapes.

Figure 12 Left: Edible schoolyard in Rotterdam, Netherlands. Right: Edible park "Alchimistenpark" in Kirchberg am Wagram, Österreich (Own image)

"*Implementing food forests is the easy part. Making them work socially and economically is the hard part. So we are basically not in the business of changing the landscape, we are in the business of changing the people* […]. *If you want to change the system you are always working with people, this works best in the city* […] *and if we change the needs of the city, we transform the countryside.*"

(Max de Corte, founder of the "Coöperatie Ondergrond", 2022)

Farmer's acceptance of trees and hedges in agricultural landscape represents another challenge for the social adoption of food forests. It was suggested that a step-by-step transition originating from agricultural stakeholders can arise, with the knowledge of traditional agroforestry systems, generational changes and communication with farmers. The farmers’ confidence must be strengthened through the presentation of good examples, political support, tangible monetary revenues, and the possibility to use machinery. Especially the given political circumstances influence the adoption of food forests by farmers, as the management and implementation of trees on agricultural land underlies certain restrictions in several European countries. Furthermore, certified organic farms require certified organic tree nurseries for food forest implementation, of which there are currently not enough, according to food foresters.

“*Maybe we should stop seeing food forests as an agriculture (sub)system since it is not only providing us with food but also with many other ecosystem services. So it is also our CO_2 accumulating machine, a biodiversity stimulator and protector as well as our water management system.*“
(Maurice Ramaker, manager of “Den Food Bosch“, 2022)

Marketing strategies
The complex, dynamic and unique character of food forests also requires unique marketing strategies. While educational public outreach might help to establish a social acceptance of new products and diets associated with food forests, other marketing challenges for food forests arise from their successional development, which is unique for an agricultural production system. It must be considered that the main crops of food forests are constantly changing during the succession. As an example, the main products from the food forest might be different berries and vegetables in the first 10 years, followed by fruit tree crops, which then again are replaced by different nut tree crops after 30 years or more. This complicates product processing and marketing. Producer associations and centralized processing facilities can potentially mitigate the challenge of high investment costs for processing machinery, which is only required in a certain period.

Besides the changing supply of main crops, food forests normally offer a wide spectrum of other crops, which are complex to market due to the small quantities produced. It is possible to focus exclusively on main crops and use the rest of the harvest for self-sufficiency. Revenues from side products, however, can also be realized through alternative marketing strategies, such as a CSA, partnerships with restaurants, food coops or direct sale. In a CSA, product supply for the members can be adapted more flexible to the current harvest from the food forest. They were furthermore recommended to create ideal conditions for empowering people by providing educational programs. According to some food foresters, working together with gastronomy often turns out to be complicated due to their inflexibility. In the cooperation between the “Voesdselbos Ketelbroek“ and the 5-star restaurant the “De Nieuwe Winkel“, however, the chef adapts the menu to the weekly available harvest from the food forest.

The possibility of creating a European wide food forest certificate, which would verify the origin of food forest products holds both an opportunity for food forest marketing, and a potential downside. Restaurant, companies, vineyards or other agricultural enterprises could advertise products in connection with a food forest they financially support or use for production with a label that consumers can rely on. Smaller food forest entrepreneurs on the other hand fear that they could potentially get excluded from this benefit due to emerging label costs.

Investment and revenues

“*A food forest is an investment for the longer term. But our patience and commitment (even from enthusiastic food foresters) is limited. The same goes for the financial market. An investment needs to become profitable or be paid back within 10 or 15 years. At that moment, a nut tree is just starting with its production acceleration. In other words, we need a long (read 25, 50, 100 years) term vision because we are limited by the short-term approach of our economy*.“

(Maurice Ramaker, manager of “Den Food Bosch“, 2022)

Food forest implementation is a long-term investment that is accompanied by high implementation costs in the beginning and a late return on investment. Land purchase, a surrounding fence and on-site infrastructure often represent the highest expenses during food forest implementation but are inevitable for many sites. Land use regulation often limit tree planting on leased land, leading to the necessity of purchasing land or cooperating with owners.

To reduce the initial investment costs, the implementation of the food forest can be distributed over several years. An external funding through companies, organizations or municipalities that are obligated to support social engagement projects or compensate emissions, is also a viable option. Especially in public food forests, expenses can also be balanced through private investors, which are encouraged by entering a tree partnership. Tree adoption schemes help to involve people into projects and raises awareness. In return for financing the tree plantation, people are provided with GPS-data and annual tree updates. The reforestation program at the "ALTA BADIA Food Forest" succeeded to plant 6000 trees in their reforestation program financed through the sale of tree partnerships. The inclusion of monetary capital from different partnerships and investors was furthermore suggested to increase the significance of food forest projects with regard to the high financial pressure on properties, which is especially important in urban areas.

Experts suggested that the use of pioneer species from collected cuttings and the creation of an own tree nursery can reduce investment costs for planting material in the beginning and ensure the fast acquisition of experience and knowledge. The general use of locally available resources was further mentioned to enhance the ecological significance of the project and reduce the overall implementation costs.

First revenues in a food forest can normally be generated after three to five years, depending on the implementation method (distributed or at once) and the desired main crop (focus on herbaceous, shrub or tree layer). The resulting income gap and negative cash flow within the first years can be ignored when sufficient financial support or own capital exists or when the food forest only represents a site business. If fast revenues are expected, this gap might be filled by starting an annual vegetable, perennial vegetable, cut flower or Christmas tree production in between tree rows. Newly planted trees would simultaneously benefit from the necessary irrigation for vegetables and cut flowers. If necessary, livestock can be used to clear the area prior implementation. Afterwards they would eventually lead to higher costs for tree protection. A combination with honey production is profitable in an evolving food forest but was mentioned to potentially influence the wild bee population negatively.

5 Discussion

5.1 Sustainability of food forests

Results from the sustainability assessment indicate, that food forests are performing well on social-environmental criteria but are lacking on economic criteria. This generally aligns with the findings of Albrecht and Wiek (2021a). Despite slight differences in sustainability criteria, particularly economic criteria, both studies produced similar outcomes. This study found that food forests have the highest sustainability score in biodiversity restoration and conservation, while Albrecht and Wiek (2021a) found that they mainly contribute to capacity building. As food forests often function in unique ways, those different findings can be explained by differences in sample size and the selected food forests for the studies.

Environmental sustainability

The overall high performance on environmental sustainability criteria of food forests in this study corresponds with various studies on agroforestry systems (Jose 2009, Lovell et al. 2018, Torralba et al. 2016, Wartman et al. 2018). Results from Park et al. (2018) and Albrecht and Wiek (2021a) further confirm that food forests support biodiversity, wildlife as well as soil and water conservation.

The low performance on the “Environmental Criteria F - Local climate regulation“ represents the only weak result within the social-environmental section of the sustainability assessment. (Fig. 43). This can be explained by the young age of many of the investigated food forest. If the canopy tree layer is not sufficiently developed or absent, it does not provide cooling for the understory. Poor climate regulation was only found in small food forests (<0.5 ha), supporting the idea that the definition of food forests should be adapted to include a minimum size of 0.5 ha and a canopy cover of at least 10% in order to provide forest-like ecosystem services (Chazdon et al. 2016, FAO 2000a).

Social-cultural sustainability

Positive effects on community well-being are especially well documented for urban and community food forests (Allen and Mason 2021, Riolo 2019). Eiden (2021) reviewed that social connection and place identification are the most commonly mentioned cultural services provided by community food forests. Community food forests contribute to well-being through recreational and educational values, social interactions, and the production of healthy and regional food, while private food forests mainly contribute through food production and job creation. In both cases, educational activities represent an important cultural service provided by food forests, with their importance often being neglected. As research suggests, that people's attitude towards the environment might be influenced by their perception and their sense of belonging to nature, environmental education in food forests might play an important role in reconnecting people with nature and thereby mitigating climate change from the bottom up (Schultz et al. 2004). A case study by Hammarsten et al. (2019) supports this idea, suggesting that exposure to food forests can develop children's ecological literacy by developing practical skills, increasing their biological and ecological knowledge, and fostering their ability to coexist and care for the ecosystem.

The location of food forests mainly determines if social-cultural sustainability services can be provided successfully. While remote locations might still provide the community with healthy food, they rarely provide an attractive space for social interactions.

Economic sustainability

While previous research on food forests has primarily focused on their social-cultural and environmental benefits, their economic sustainability has received limited attention. According to Albrecht and Wiek (2021a), the low performance on economic sustainability criteria can be attributed to the young age (<5 years) of some of the studied food forests (30%). This finding is consistent with the results of the present study, where approximately 30% of the investigated food forests were less than 5 years old and still developing their economic viability (Fig. 5). Many food forest crops only reach their main production phase after 15 years or even later. The small size (>0.5 ha) of 12 of the 30 studied food forests may also explain the low performance on economic sustainability criteria. Although this study found no general correlation between size and economic viability, food forests smaller than 0,5 ha tend to lack economic viability.

Eight of the studied community food forests and some other food forests were not designed with a primary focus on economic viability. Many operators aim to improve local food security and run the food forest as a side business alongside their main jobs. Education was one of the two main services cited by 37% of the food forests, and revenues from tours, courses, and presentations were often reported to be insufficient to cover expenses. Consequently, a research focus on food forests with the exclusive goal to create a successful business model would have likely shown an enhanced overall performance on economic sustainability criteria. However, the focus of this study was to provide a general overview of food forests and their potential in Europe. To better assess the economic sustainability of food forests in further research, an in-depth economic analysis with full cost accounting is required.

5.2 Connecting food forests and the Sustainable Development Goals

The sustainability assessment showed that food forests can be classified as environmentally and socially sustainable land use systems and can therefore play a role in accomplishing the SDGs. For each of the 17 SDGs the UN formulated sub targets which include number-designated “Outcome“ (circumstances to be attained) and letter-designated “Means of Implementation“ (MoI) targets (Bartram et al. 2018). The MoI targets do not address the actual goals but provide advice and guidelines for states and other relevant actors on how to adopt policies and mobilize financial resources to support the SDGs (UNDP 2014). Evaluating the role of agricultural systems in achieving the SDGs apart from policy guidelines by using the MoI targets is insufficient, as they are not formulated for such approaches (UNDP 2014). This study therefore evaluates the role of food forests in accomplishing the SDGs by comparing the outcomes they deliver with the “Outcome“ sub targets formulated in the SDGs. Their contribution and the respective sub targets are described in the following according to each of the 9 SDGs (Sachs 2015):

Goal 2: End hunger and promote sustainable agriculture

“This goal is complex: to end hunger, improve nutrition, and ensure that the farm system is resilient to environmental stresses but also less destructive to the environment.“ (Sachs 2015).

- 2.1 Ensure access to safe, nutritious food
- 2.2 End malnutrition
- 2.3 Support small-scale food producers
- 2.4 Implement resilient agricultural practices (Compare goal 13)
- 2.5 Maintain biodiversity and wildlife (Compare goal 15)

This study shows that food forests enhance local food security by supporting self-sufficiency. Due to their high diversity of edible plants, they can help in diversifying diets, adding value for small-scale producers and maintain biodiversity and wildlife (Albrecht and Wiek 2021a, Björklund et al. 2019, Nytofte and Henriksen 2019). Food forests represent multifunctional land use systems that are resilient to environmental stresses and changes regarding the production of food (Malézieux 2012, Waldron et al. 2017). Their wider implementation therefore ensures access to safe and nutritious food for future generations.

Goal 3: Ensure healthy lives and promote well-being for all

The goal is to reduce the under-5 mortality rate to below 25 per 1.000 live births and to ensure universal health coverage and healthy lives and well-being for everyone (Sachs 2015).

- 3.4 Promote mental health and well-being
- 3.9 Reduce deaths and illnesses to air, water and soil pollution (Compare goal 6)

Most of the investigated food forests contribute to community well-being in various ways (Albrecht and Wiek 2021a, Hammarsten et al. 2019, Riolo 2019). The effects of green environments, especially in urban areas, are known to be positively correlated with mental healthiness (Beyer et al. 2014, Pálsdóttir et al. 2018, Wolf et al. 2020). Edible greens in urban areas and food forests can offer nutritional and healthy food, educational and recreational activities, retreat areas and meaningful employment (Hammarsten et al. 2019, Nytofte and Henriksen 2019, Riolo 2019). Especially in socio-economically challenged areas, food forests might help to strengthen the local community (Stoltz and Schaffer 2018).

Goal 4: Ensure quality education and promote lifelong learning opportunities
One of the linchpins for achieving the SDGs will be access to quality education for everyone (Sachs 2015).

- 4.2 Ensure quality early childhood education and development
- 4.7 Ensure knowledge and skill acquirement needed to promote sustainable development (Compare goal 12, 13)

Food forests offer capacity building in terms of climate change mitigation, practical competences and ecological understanding (Hammarsten et al. 2019). In this study, education was one of the main services for 37% of the food forests. While capacity building in community food forest is usually free for everyone, private food forests often charge small amounts for educational events.

Goal 6: Ensure availability and sustainable management of water and sanitation
"This goal seeks to ensure that every person has access to safe and affordable drinking water, as well as sanitation and hygiene. The goal also calls for large strides in reducing water pollution and raising the efficiency of water use." (Sachs 2015).

- 6.1 Ensure access to safe drinking water
- 6.2 Improve water quality (Compare goal 3)
- 6.4 Increase water-use efficiency.

Food forests in this study performed well in terms of water conservation through rainwater harvesting, water retention areas, mulching and the creation of cool microclimates. They are only depended on external water inputs during their juvenile stage and begin to be more self-regulating as they evolve. Therefore, they have the potential to outperform annual cropping systems in terms of water-use efficiency when calculating over their whole lifespan.

Stormwater runoff from industrial agriculture and urban areas often leads to surface- and groundwater pollution, which influences water quality negatively (Ongley 1996, Oquist et al. 2007, Seitz and Escobedo 2008). This impact can be reduced by involving trees into cropping systems and urban areas (Armson et al. 2013, Seitz and Escobedo 2008, Zhu et al. 2020).

Goal 8: Promote sustainable economic growth and decent work for all
SDG 8 represents the economic development goal. Its targets to raise the income per person, emphasize full employment, decent work, labor rights as well as to end modern slavery and human trafficking (Sachs 2015).

- 8.5 Achieve decent work for all

Food forests are rarely able to provide a livelihood if they are not funded externally but offer purposeful employment and decent work. However, in the SDG 8 it is criticized, that the goal for sustainable economic growth does not acknowledge planetary boundaries and is prioritized over ecological integrity and absolute reduction of resource use, which would be necessary for achieving a sustainable transition especially in the Global North (Eisenmenger et al. 2020, Foley 2011, Steffen et al. 2015). The striving for economic growth in the SDG 8 therefore contradicts with other SDGs.

Goal 11: Make cities and human settlements sustainable
"This goal represents the recognition of central governments that cities should pursue sustainable development in their own right." (Sachs 2015).

- 11.3 Enhance sustainable human settlement planning (Compare goal 15)
- 11.7 Provide access to safe, inclusive and accessible, green and public spaces

Making cities and communities sustainable involves the implementation of green infrastructure. Edible green infrastructure in urban areas, including community food forests, integrates various principles of sustainability by contributing to food security, landscape multifunctionality and resilience, climate adaption as well as social inclusion (Cariñanos et al. 2022, Clark and Nicholas 2013, Konijnendijk and Park 2020, Riolo 2019, Russo and Cirella 2019). Research by Schafer et al. (2019) and Lehmann et al. (2019) furthermore provides first evidence, that urban and peri-urban food forests are not inferior to other urban green infrastructure in terms of C storage potential, but simultaneously provide several other benefits. In contrast to rural areas, urban food forests have the potential to close open nutrient loops between consumers and food production site (Taylor and Lovell 2021). Green infrastructure in urban areas is also important in managing rising temperatures as they provide regional cooling (Armson et al. 2012, Lanza and Stone Jr 2016, Rosenfeld et al. 1998). The effects of edible green infrastructure are therefore additionally addressing the SDG 2, 3, 12 and 13, wherefore its potential is getting recognized in various cities around the globe (Konijnendijk and Park 2020, Russo and Cirella 2019). Furthermore, urban food forests have the potential to support the local population during a given isolation, such as a natural catastrophe or a siege of a city during a war scenario.

However, Säumel et al. (2012) and Ferreira et al. (2018) mention that food production in urban environments harbors the risk of food contamination through pollution. Gori et al. (2019) found, that trees translocate fewer heavy metals from soils to edible parts than annual vegetables and other herbaceous crops. Heavy metal uptake in plants can be minimized through right species selection, which is determined by the dispose strategy of the plant, and vegetation or other physical barriers between tree crops and roads (Gori et al. 2019, Säumel et al. 2012).

Goal 12: Ensure sustainable consumption and production patterns

“The main idea of SDG 12 is to promote the ‘circular economy’, in which today’s wastes become tomorrow’s inputs and recycled product. […] “ (Sachs 2015). This also includes reducing the release of industrial chemicals into the environment and reducing food wastes in production and supply chains (Sachs 2015).

- 12.3 Reduce food loss along production and supply chains
- 12.8 Ensure dissemination of information for sustainable development (Compare with goal 4, 13)

Circular economy relies on a holistic waste and recycling management, aiming to optimize the use of resources. Strengthening local and seasonal food production in short-supply chains as well as balancing nutrient fluxes presents an important tool to minimize waste and resource use on different levels of the value chain (COM 2013, De Schutter 2014, Jurgilevich et al. 2016). Matured food forests are characterized as low-input farming systems without the use of industrial chemicals and have the potential to balance global nutrient fluxes through closing local nutrient cycles (Jacke and Toensmeier 2005). If food forests would increase in number and size, their altered contribution to the food system would promote circular economy.

Goal 13: Take urgent action to combat climate change and its impacts

The shared focus of this goal lies on emphasizing mitigation and adaption to climate change (Sachs 2015).

- 13.1 Strengthen resilience and adaptive capacity to climate-related hazards (Compare goal 2)
- 13.2 Reduce total GHG emissions
- 13.3 Improve education and awareness-raising on climate change mitigation and adaptation (Compare goal 4, 12)

Besides raising awareness on climate change mitigation, well managed and implemented food forests take urgent climate action through above- and belowground C-sequestration (Lehmann et al. 2019, Nair et al. 2010, Schafer et al. 2019).

Goal 15: Protect and restore terrestrial ecosystems, sustainably manage forests, combat desertification, and halt biodiversity loss

“This crucial goal recognizes all of the threats to terrestrial ecosystems and biodiversity around the world. […]“ (Sachs 2015).

- 15.1 Conservation and restoration of terrestrial ecosystems
- 15.2 Promote the implementation of sustainable management of all types of forests
- 15.3 Combat land degradation
- 15.5 Halt the loss of biodiversity (Compare goal 2)
- 15.9 Integrate ecosystem and biodiversity values into planning (Compare goal 11)

Food forests investigated by Albrecht and Wiek (2021a) and in this study performed well on ecological sustainability criteria including biodiversity, wildlife-habitat conservation, and prevention of land degradation. Research by Park et al. (2018) furthermore describes the potential of food forests to assist in ecological restoration. The prevention of invasive species, which is also mentioned as a sub-target of the SDG 15, is often not considered in food forests (Sachs 2015).

Summary

A total of nine SDGs, including 25 of 126 formulated “Outcome“ sub targets, were found to be positively influenced by the characteristics or impacts of food forests (Fig. 13).

Figure 13 Contribution of food forests to the sub targets of the 17 SDGs by means of four different levels. From the inside out: First ring green indicates a contribution to one sub target; Second ring green to two sub targets; Third ring green to half of the sub targets; Every ring green to all sub targets of the respective SDG. (Own illustration)

As multifunctional and resilient land-use systems, food forests can support a sustainable transition in both agricultural production systems and urban areas. While they cannot address every sub-target of the nine SDGs presented, they contribute at least partly to all of them. Visser et al. (2019) suggest that a healthy soil provides the foundation for successfully realizing and implementing all SDGs. As food forests place particular emphasis on soil conservation and preservation, they should be considered as an important tool for achieving the SDGs and integrated into intergovernmental and regional strategies.

However, food forests tend to focus on operating within planetary boundaries and creating edible landscapes for future generations while neglecting economic growth. Although some authors mention this focus as necessary for achieving sustainable development, the widespread adoption of food forests in Europe is largely dependent on their ability to finance themselves (Ott and Döring 2011). As a result, the lack of economic viability of food forests limits their contribution to achieving the SDGs and a sustainable food system. Chapter 5.3 provides a detailed analysis of the factors that influence the adoption of food forests in Europe and offers guidance for addressing this limitation, among others.

5.3 Potential contribution towards a sustainable food system

So far, this study highlighted the sustainability of food forests and thereby warranted their contribution towards a sustainable food system. However, their current contribution appears to be low, as only 12% of investigated food forests prioritize food production and an even smaller proportion focuses on actual sales. Food forests typically prioritize local self-sufficiency and educational programs over increasing their food supply to the food system. Björklund et al. (2019) mention, that food forests must increase in size if they want to contribute to more than local self-sufficiency. Upscaling of food forests especially close to densely populated areas would help to enhance their economic viability and increase the food supply from food forests. However, as food forests intentionally use short supply chains within the local community to exploit their full social and ecological potential, an increase in number of food forests, rather than only in size, would be necessary to enhance their contribution towards a sustainable food system.

Despite the scientifically demonstrated benefits, the adoption of food forests remains low, facing challenges similar to common agroforestry or other innovative systems, such as high implementation costs, lack of knowledge and experience, inadequate policies, and management challenges (Rosati et al. 2021, Valdivia et al. 2012, Wilson and Lovell 2016). This study reveals that for food forests the social acceptance of the system, product marketing as well as late return of investment pose additional challenges, impacting the wider adoption of food forests and their contribution towards the food system.

Financing food forests

The lack of economic viability in the early years after implementation often hinders investors and entrepreneurs to create food forests as a primary business. The short-term approach of the current economic mindset contradicts with the long-term vision of food forest projects that aim to create sustainable production systems for future generations (Albrecht and Wiek 2021b). As a result, most existing food forests are organized as nonprofit organizations, private side businesses or community food forests in public spaces, instead of main businesses with a primary focus on food production (Albrecht and Wiek 2021a, b, Salbitano et al. 2019).

The low economic viability of food forests could be enhanced by monetizing the value of ecosystem services or environmental protection (Albrecht and Wiek 2021a, Fiebrig et al. 2020, Rosati et al. 2021). Monetizing ecosystem services, depending on their actual value to human welfare and the global economy, is expected to fundamentally change the global price system and resource management (Costanza et al. 1997). However, incorrect valuations of ecosystem services, particularly in unstable markets, as well as inadequate framework conditions and controls, complicate implementation (Silvertown 2015). Nevertheless, food forests can be partially funded through monetized ecosystem services, such as carbon sequestration and biodiversity restoration. A locally coordinated concept that provides compensation at the source, along with appropriate conditions and controls, is necessary to ensure the sustainability of compensation strategies.

Even though external financial support is crucial for successful food forest implementation, the long-term goal should be to achieve monetary independence from governmental subsidies (Albrecht and Wiek 2021b, Park et al. 2018). It can be sustainable to monetize the value of ecosystem services or environmental protection, but a business concept is not sustainable if it is permanently dependent on subsidies. A graduated financial support within the first years seems suitable to cover high implementation costs and over bridge the initial income gap. In the Netherlands, where the necessity of ecosystem restoration is especially high due to the impact of industrial agriculture and the relative low forest tree cover, food forest implementation is already being subsidized as part of the "*European Green Deal*" (EAA 2022b, Green Deal 2017). However, current governmental subsidies are not sufficient to cover full implementation costs and are not available in most of the European countries.

For successful and sustainable food forest implementation, strong partnerships and cooperation, based on shared values and visions like mitigating climate change, creating a sustainable food system or cultivating new varieties of food, are therefore required (Albrecht and Wiek 2021b, Wartman et al. 2018). This allows the environmental and social goals of food forests to be combined with economic viability. A partnership with municipalities, for example, can help to reduce rental fees. Cooperation with public institutions or social entrepreneurships that share the same interest can bring mutual economic and ecologic benefits. Private investments obtained through CSA-members or tree partnership can help to share the risks and benefits of food production between consumer and producer. As food forests can offer multiple sources of income, including niche products, workshops, tours, events, etc., they also offer the possibility to create partnerships in various sectors. To fully utilize these possibilities, a sustainable business training, especially in terms of networking, fundraising, and collaborating with other organizations, is beneficial for food foresters (Albrecht and Wiek 2021b, LeBlanc et al. 2014). Participation in transfer workshops, different networks and conferences on agroecological topics, can help food forest entrepreneurs to accumulate knowledge and identify potential partners (Albrecht and Wiek 2020).

Promoting food forests into mainstream

The promotion of agroforestry systems into mainstream is thought to require research, dissemination of information and adequate policies (Smith et al. 2012). In contrast to common temperate agroforestry systems, crops in matured food forest represent exclusively perennial instead of annual carbohydrate sources. A higher food supply from food forests would partly imply a change in human diet towards a higher consumption of perennial greens and different nuts. The scientific evidence, that highlights the benefits of a stronger plant-based diet for human health and well-being as well as for the environment can support the social acceptance of food forests (Campbell and Campbell 2007, Horton et al. 2014, Leitzmann and Keller 2020, Willett et al. 2019). Especially nuts represent a product from food forests with a high demand in Europe and well documented benefits on human health (CBI 2018, Martini et al. 2021). In 2021, the EU imported $7.2 billion in tree nuts mainly from the United States, Turkey, Vietnam, Chile and Iran (USDA 2021). The growing demand for nuts and the negative environmental impact of their production overseas should encourage investors and agricultural entrepreneurs to stronger support local nut production in food forests. The manual labor required in these systems creates opportunities for new jobs in a pleasant working environment, but also causes additional costs compared to overseas production. Since more local nut production would shorten supply chains and increase Europe's food self-sufficiency, policy makers should be interested in offsetting the additional costs incurred (Enriquez 2020).

Besides the production of well-known nuts, food forests also offer various unknown and rarely used products, particularly perennial greens. A lack of research about the nutritional value of new perennial food sources from the food forest limits its wider acceptance (Kumar et al. 2015, Leisner 2020). However, the nutritional yield from food forests appears promising (Nytofte and Henriksen 2019). The promotion of new products through different platforms, research, and education about food forest benefits is needed for wider food forest adoption. Creating public food forests with the involvement of the local community is the most promising way to raise awareness within society (Nytofte and Henriksen 2019). Through integration, society can be sensitized to new products and the relationships between ecological processes, food production and climate change.

Especially municipalities and policy makers are summoned to structurally accompany the transition from spatial segregated land-use systems towards socially inclusive, multifunctional systems. As requested in the SDG 11, cities and communities should pursue sustainable development autonomously (Sachs 2015). Supplying parks, schoolyards, gardens, waysides, and recently destroyed forests, such as those affected by the bark beetle (*Scolytinae*), with edible plants can help society regain a connection to the food system by providing the opportunities to collect their own food (Hlásny et al. 2021). The habit of collecting food from nature has been lost in many parts of Europe during the last half of the century due to growing economic wealth and the loss of edible landscapes (Poschlod 2017). To revive this habit, education about the impact of our current food system and the demonstration of alternatives is necessary. The reconnection between producers and consumers builds the essential social foundation for the creation of a sustainable food system (FAO 2018, Willett et al. 2019). Food foresters are often aware of this and therefore offer educational programs to address this important gap (Fig. 6). They see the necessity of integrating the local community into projects to promote their adoption into mainstream and support a sustainable development.

However, more experienced consultants to accompany municipalities and more educated managers to oversee public food forests are needed to realize their implementation. Additionally, volunteers and participants are needed to support the managers and consultants in implementing and maintaining public food forests (Riolo 2019). Their willingness to participate can be strengthened by highlighting the projects importance for the provision of ecosystem services and the benefits for the local community (Tiraieyari et al. 2019). Taylor and Lovell (2021) created a preliminary framework consisting of guidelines and strategies for creating public food forests. With the help of such guidelines and the experience of food forest pioneers, officially recognized training programs for public food forest managers must be established. Municipalities can finance these newly created manager jobs and food forest implementation through different funding programs as part of the "*European Green Deal*" in order to create sustainable cities and communities (EC 2019).

Scaling up food forests

Besides promoting food forests in urban areas by increasing their number, the overall cultivation area of food forests must increase to meaningfully impact the food system. Upscaling food forests can improve their economic viability if the challenges in management can be overcome successfully (Björklund et al. 2019). Similar to other studies, it was found that the high diversity and complexity of food forests is a major barrier concerning their management (Björklund et al. 2019). Creating a structured design and focusing on a few main crops in a large food forest, as it is often the case in tropical food forests, are opportunities to simplify workflows and product marketing, leading to an enhanced economic viability (Belcher et al. 2005). The main challenge in designing large food forests is thereby combining the ecosystem services derived from their complexity and diversity with the requirements for simplified workflows to achieve economic viability (Rosati et al. 2021).

The “Schijndel Food Forest“ project in the Netherlands, initiated in 2018 by “Voedselbosbouw Nederland“ and still being implemented, is currently one of the largest commercial food forests in Europe with the goal of proving the economic viability of a simplified food forest design. The 20 ha design, with 12 different species per ha, is divided into 17 ha productive area and 3 ha for hedges, water features, and pathways (Groot et al. 2019). The 3 ha are designed to promote biodiversity, with the goal of compensating for the loss of biodiversity in the productive area. Like the “Food Forest Schijndel“, other simplified food forest designs should consist of an area that compensates for the loss of biodiversity to create an ecosystem that regulates itself over time in terms of pests and diseases, nutrient cycles and water management (Altieri 1999, Malézieux 2012). This area should consist of landscape features that offer diverse habitats and plants for insects, birds and other wildlife. Those features can include water ponds and small streams, deadwood components, bare mounds, small hills and inlets as well as a high diversity of plants (Fig. 14).

Figure 14 Different habitats for insects, birds and other wildlife in food forests (Own image)

The compensation area can be implemented as a wind hedge to protect the productive area of the food forest and can be used for own consumption. As a wild or “romantic“ arranged food forest it can be integrated in the marketing strategy as a place to organize workshops, tours and events. The required size is dependent on the location of the food forest, especially its connection to green corridors (Jose 2012). Its implementation costs can be reduced by using seeds and cuttings of locally sourced pioneer species. Starting the whole food forest plantation with pioneer species, that get pruned and cut down once they fulfilled their ecological role, increases species diversity and furthermore helps to shift the soil characteristics towards a forest-like ecosystem (Bugg et al. 2011, Corenblit et al. 2018, Susyan et al. 2011, Wilson and Lovell 2016).

However, the right management of pioneer species requires specific training, as the whole design and management of food forests does (Albrecht and Wiek 2021b). The large number of different species and the complex development of food forests requires knowledge and skills in various subject areas. Gathering experience through volunteering or working in other food forests and exchanging knowledge with experienced farmers can be valuable before starting a food forest project. However, management practices must often be adapted to the specific site characteristics. Information on complex plant combinations within a multi-layered polyculture system, suited for the local conditions, are difficult to find and therefore often require trial and error testing (Albrecht and Wiek 2021b, Lovell et al. 2018). A general lack of research about food forest management and design further complicates knowledge acquisition and often leads to contradicting management practices applied, such as the performance of fruit tree pruning or the use of pioneer species (Fiebrig et al. 2020). Comprehensive research on plant compositions and food forest practices is needed to increase the overall success rate of food forest implementation (Albrecht and Wiek 2021b). However, every different approach, whether successful or not, can contribute to the existing knowledge base if it is shared.

Land for food forest conversion

The catchment area of food forests determines their economic viability and if their provided benefits for society can be used comprehensively. While Belcher et al. (2005) describe remote areas appropriate for food forest implementation in the tropics, the contrary is the case in Europe. Placing food forests in urban public spaces, close to cities or as part of a CSA ensures a large catchment area and increases the success rate of a food forest project.

Björklund et al. (2019) furthermore suggest the conversion of margin land and transition areas between different land use as appropriate. Specifically on margin land or degraded farmland, the ecological benefits of food forests as a land restoration approach and an agricultural production system can be fully exploited as they help to stabilize soil, retain nutrients and prevent erosion (De Vries et al. 2013, Molnar et al. 2013, Park et al. 2018). Existing farms can also convert small plots of available land into food forests without suffering from the initial income gap. Integrating food forests into the edge zones between forests, pastures, arable land, or residential areas can provide ecological and economic benefits without affecting the rest of the farm's productivity (Björklund et al. 2019). For agricultural direct marketing strategies, small harvest quantities from food forest crops can become marketable, providing diversification and product expansion.

However, implementation costs, inadequate policies, farmers' perspectives and time for management often limit food forest adoption on existing agricultural land (Molnar et al. 2013, Rosati et al. 2021). Farmers may lack confidence due to the absence of mature and structured food forests that serve as demonstration sites (Rosati et al. 2021). In Europe, currently only wild or "romantic" arranged food forest, which are often uninteresting for commercial agricultural production, can serve as demonstration sites, while structured food forests are still young (<15 years) and have yet to prove themselves as an agricultural production system.

Therefore, the conversion of land into food forests may not come primarily from agricultural entrepreneurs but instead be initiated by stakeholders not associated with agriculture. Newcomers with a different background are often not subjected to economically or ecologically learned constrains and therefore show more tolerance for perennial polycultures in agricultural landscapes. They, however, face difficulties in purchasing agricultural land and are often dependent on landowners as cooperation partners. A cooperation between food forest pioneers and established farmers can bring mutual benefits by combining available resources and capital with innovative ideas and knowledge. To enable both farmers and other pioneers to implement food forests for agricultural production, a checklist with important key points that should be considered for planning and implementing new projects is provided in the appendix C.

5.4 Further research recommendations

As already mentioned, the adoption and acceptance of food forests in society is often dependent on available scientific evidence of their advantages and disadvantages (Nytofte and Henriksen 2019, Smith et al. 2012, Wartman et al. 2018). In contrast to the body of research that addresses modern agricultural land-use systems, research about food forests as such systems is still at a nascent stage. With this lack of evidence, food forest pioneers have to resort to their own experience. Most learnings come from trial and error, from other practitioners or general assumptions of the system, rather than solid evidence (Albrecht and Wiek 2021b).

Adequate research on perennial cropping systems is challenging due to the extended period required to fully assess their effects. As food forests start to generate first revenues after three to five years, their minimum research duration must extend this period. Thorough examination of the economic viability, the performance of plant growth and plant interactions in food forests demands sustained funding, which again conflicts with the short-term perspective of our present economic system (Lovell et al. 2018). Despite these difficulties, continued research is necessary to fully understand the potential of food forests as a sustainable and equitable food production solution for future generations. The following table 3 therefore provides recommended research topics identified during this study:

Table 3 Recommended topics for further food forest research

Economic aspects	• Financial value of food forest products (including “added value“) and consumers’ willingness to pay • Identification of appropriate marketing strategies • Valuation of new marketing strategies • Harvestable and marketable yield from food forests • Nutrient composition and nutritional value of perennial edibles • Cooperation with social entrepreneurships (E.g. German “Regionalwert AG”) • Full cost accounting for different food forest projects
Design and Management	• Different design and implementation strategies of food forests • New possible technologies for harvesting food forests • Vole and field vole prevention and protection • Fungal diseases in matured food forests • The effect of intermediate disturbances and fruit tree pruning (Resources input required in contrast to obtained yield) • The identification of suitable species and cultivars for “forest climate“ (Nut tree crafting, specifically *Quercus* species)
Ecological processes	• Different tree planting methods (Compost, mulch, biochar, from seed, with pioneers etc.) • Influence of early compost application on tree and mycorrhiza cooperation • Tree grass interactions • Functional traits of plant compositions • Tree development at different locations and different soils (Size, age, growth rate etc.) • General influence of pioneer species • Shifts in the soil food web during food forest succession • Influence of honeybee on wild bee population • Biodiversity restoration and C-storage potential of food forests • Full GHG calculation for food forests
Public food forests	• Influence of public food forests in cities and communities • Integration of society into projects • Risks of food production in urban environments • Creation of training programs for consultants and managers • Possibilities for funding public projects

5.5 Strength and limitations of this study

When assessing the sustainability of food forests, it is important to keep in mind that the definition of the terms "sustainability" and "sustainable development" is often vague and complex (Jabareen 2008).The selection of criteria in this field should therefore always be scrutinized and updated based on recent research when necessary. Even though the sustainability assessment in this study was based on current scientific findings, it cannot be excluded, that the subjective valuation of the author or the participants influenced certain results (AlWaer et al. 2008, Becker 2004). Additionally, 11 out of the 30 food forests studied were not visited, meaning their sustainability assessment relied solely on conducted interviews, which could be biased by the perspectives of the interviewees. The possibility of incorrect answers due to unawareness or other circumstances cannot be ruled out. Long-term monitoring of food forests can reduce bias and improve the validity of future sustainability assessments (Park and Higgs 2018). It should also be noted that the collection of qualitative data was a new field of research for the author, even though test interviews prior the actual research were conducted. Positively, the results of this study align with a similar study in this field, lending credibility to the here obtained findings (Albrecht and Wiek 2021a).

This study provides a comprehensive overview of the current state and potential of food forests in the Oceanic and Continental climates of Europe, due to the different study areas and diverse group of interviewees. However, the diversity of climates and site characteristics made it difficult to draw an accurate comparison between different food forests and the challenges they face. The provided recommendations are standardized and thus only limitedly applicable to individual food forests. Nevertheless, with these results in mind, food foresters can analyze their given circumstances and eventually transfer relevant suggestions to their individual planning and management processes.

6 Conclusions

The aim of this study was to assess the potential and limitations of food forests to create a more sustainable food system in Europe. Therefore, data from 30 food forests, expert interviews, and site visits was collected. The focus was to identify the main services and characteristics of food forests, evaluate their sustainability in the light of the Sustainable Development Goals (SDGs), and identify factors that influence their contribution towards the food supply in Europe.

Results indicate that food forests typically prioritize local self-sufficiency, conservation of soil and biodiversity as well as educational programs over food production. They are mainly organized as nonprofit organizations, private side businesses, or community food forests in public spaces. While food forests perform well on social-cultural and environmental sustainability criteria, they often lack economic viability. Nevertheless, they contribute to nine of the seventeen SDGs, supporting adaption to climate change, conservation of soil and biodiversity, local food security, capacity building, and social inclusion. At the current state, this also demonstrates the extent to which food forests contribute to a sustainable food system, namely on a local scale through the integration of society into the process of food production. The creation of public food forests in and around urban areas represents a promising method for municipalities to increase passive food provision and support local sustainable development.

In addition to the creation of food forests in public spaces, larger projects with a simplified design and a focus on main crops offer the possibility of increasing the overall food supply from food forests. However, existing demonstration sites are too young to verify this possibility and large, simplified food forests still have to prove themselves as economically viable food production systems for agricultural landscapes. Currently, the manual labor required in food forests remains an economic constraint that must be offset by public support or financial incentives in the interest of environmental protection and regionalization of the European food system. Further research on economic models, customized marketing strategies and possible cooperation for food forests can help to increase their profitability and promote their long-term sustainability.

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Appendix

Appendix A – Interview and observation script

General food forest (FF) data:

Table 1 General food forest data (Location, Size, Age, Site, Climate)

Location	Size	Age (First year of planting)	Specific site characteristics	Local climate regulation

Part 1: Ecological

What is the initial idea or goal for the FF?

Can you give a brief history of the land use before you started planting the FF?

How long was the time from conception until first harvest or other benefits obtained from the FF?

Did you notice any changes in fauna? If yes, from when on and which changes did you observe?

What did you do for soil enhancement before planting?

What do you do for soil enhancement now?

How was your water management in the FF in the beginning?

How is your water management now?

Do you have water retention areas?

Did you consider complementary relationships between trees in your design? If yes, how did you ensure a high functional diversity?

Did you notice specific positive or negative interactions between tree species?

Do you have any problems with pests and diseases? If yes, which problems and how do you manage?

Do you have completely undisturbed areas in your FF?

Do you have a fence around the FF?

Do you do any tree pruning or did pruning on the juvenile fruit trees? If yes, do you use specific pruning techniques?

Part 2: Economical

What are the main services of the FF? Name the major 2 from below or feel free to add your own:

- Self-sufficiency
- Primary production of food
- Food processing
- Tree nursery
- Education
- Research
- Community Building
- Recreation
- Environment
- __________

Is the FF your main source of income or a side business?

Is the FF economically self-sufficient? If no, how do you finance the FF?

To what extend does the FF maintain your and/or other livelihoods?

How much you invested in the beginning?

How much time per week the FF needs your attention?

Which work concerning the FF demands most of the time?

What kind of different products does the FF produce?

What kind of different products/services do you sell related to the FF?

How do you sell your products/services?

Do you track and monitor yields and processes in the FF?

Part 3: Social

Do you have any employees or volunteer? If yes, ask employees/volunteers if possible:

- How are the working conditions in the FF?
- Are you satisfied with your employment?
- Are you taking part in decision making?
- Do you conduct events, meetings besides working?

How long do you train volunteers and employees before they do FF related work on their own?

Who manages/ plans action in the FF? If more people, please describe the process of decision-making and work-distribution

How is the FF connected with the nearby community?

How is the feedback from the community?

Who has access to the FF?

Who owns the land and the FF?

Do you participate in any kind of research project?

Part 3: Social (Additional for Community FF)

How many people participate regularly in the FF project? How many people are part of the community?

Do you train the people before they start working in the FF?

How do you inform the community about processes of the FF?

Can the Community FF provide a side business for participants? If yes, to what extend?

Part 4: Expert questions and free conversation

How can FFs alter their contribution to the food supply in Europe?

What are the limitations and biggest challenges?

- What are the limitations regarding the available products from a FF?
- What are the problems regarding the workload or complexity of the work?
- Do you see any problems regarding the acceptance from society and policy makers?

On what scale do FF have the best chance to function well and be economically reliable?

How can FF be adapted for an increased production?

What are the most important design strategies for large FF?

Which spaces should be transformed into food FF?

What are the most important research questions regarding FF?

Which plant shouldn't be missed in any FF?

Appendix B – Coding guideline

Table 2 Coding guideline for expert interviews

Category	Code	Sub-code 1	Sub-code 2	Definition
Economic viability	Reasons for high implementation costs	Land purchase		Mentioned reasons for high implementation costs
		On-site infrastructure	Water	
			Tool shed	
			Fence	
		Plant material		
	Strategies to reduce high implementation costs	Distribution of implementation		Mentioned strategies for reducing implementation costs
		Use of pioneer species from local sources		
		Creation of tree nursery		
		External funding	CSA	Mentioned external funding strategies to cover implementation costs
			Compensatory measures for companies, organizations, municipalities, governments	
			Tree adoption scheme	
	Reasons for late monetary revenues	Yield gap for tree crops in first years		Mentioned reasons for late monetary revenues
	Strategies to bridge the yield gap	Production of other products during yield gap	Annual/ Perennial vegetable production	Mentioned strategies to bridge the yield gap through

			Christmas trees production	production of goods
			Livestock	
			Cut flower production	
		External funding	CSA	Mentioned external funding strategies to bridge the yield gap
			Compensatory measures for companies, organizations, municipalities, governments	
			Tree adoption scheme	
	Difficulties in product marketing	Diversity of products	Small harvest quantities	Mentioned reasons for problems with product marketing due to character of food forests
			Different harvest times	
			Change of products during succession	
	Potential marketing strategies	Fruit-CSA		Mentioned strategies for mitigating product marketing problems due to character of food forests
		Direct sales		
		Self-picking model		
		Cooperation with restaurants and food coops		
		Integration of main crops		
Management practices	Challenges due to character of food forests	Not suitable for mechanized workflows		Mentioned management challenges that arise through the character of food forests
		Complex and diverse system	Long training periods required for workers	

			Lot of manual labor	
			Knowledge in various sectors required	
	Strategies to improve management processes	Linear structured design		Mentioned strategies for improving management processes
		Reduced diversity		
		Potentially new technologies for harvest		
		Training for food foresters		
	Challenges for new tree plantings	Increase of global water scarcity	Capacity to water	Mentioned challenges for new tree plantings
			Access to water	
		Concurrence with grass		
		Frequent weeding required		
	Strategies to improve the success of tree planting	Use of pioneer species		Mentioned strategies for improving the success of new tree plantings
		Good water conservation strategy before planting	Creation of water retention areas	
			Synergy between watering vegetables for yield gap and tree growth	
			Improvement of soil structure through Bentonit and Charcole	

		Use of organic mulch		
	Challenges due to external factors	Extreme weather events		Mentioned management problems that can be caused by external factors
		Pest and disease		
Social acceptance	Challenges for the social adoption of products	Unknown and strange products	Fear of new products	Mentioned reasons that complicate the adoption of food forest products by society
			Long progress of customization for new products	
			Some products are perceived as strange	
		Only perennial instead of annual carbonhydrate sources partly requires a change in diet		
		High prices		
	Strategies to increase social adoption	Presentation of new products	Social-media	Mentioned strategies to increase the overall social adoption of food forests
			Television	
			Famous chefs	
		Education about food forest benefits		
		Creation of public food forests		
		Enhance design aesthetics		
		Creation of food forest label		

	Reasons low food forest adoption by farmers	Lack of demonstration sites		Mentioned factors that complicate the adoption of food forests by farmers on existing farmland
		Lack of political support		
		Lack of organically certified tree nurseries		
		Restrictions for tree planting of farmland		

Appendix C – Checklist for food forest implementation

Before implementation:

1. Creation of contacts with other food foresters (nearby or elsewhere in the country) with the help of internet research or other food foresters from Table 2
2. Participation in food forest and permaculture networks e.g. The Agroforestry and Forest Garden Network
3. Collection of knowledge from food forest books e.g. the two volumes of "*Edible Forest Gardens*" by Dave Jacke and Eric Toensmeier, published in 2005
4. Training and education in other food forests (From young to matured food forests) If possible: Simultaneously collect seeds and plants from other food forests for own tree nursery

   If not possible: Hire consultants or invite experts from other food forests
5. Participation in transfer workshops and conferences on agroecological topics
6. Identification of available and suitable sites for implementation (Large catchment area can enhance success rate)
7. Land purchase or contract with partners that share long-term visions and goals
8. Observation and research on climate, soil conditions, site characteristics, wind directions, sun paths, natural surrounding flora and fauna, available water supply, catchment area and community (Ideal for one year)
9. Identification of possible markets in surrounding community:
   - CSA
   - Restaurants
   - Direct sales
   - Food coops
   - Self-picking
   - Etc…
10. Identification of product gaps in the market and identification of main products for the food forest (Consider the changing products due to the successional character of the food forest)
11. Identification of possible partnerships for financing implementation
    - Private investors (Tree adoption scheme)
    - Organizations or companies that are obligated to compensatory measures

- Public institutions or social entrepreneurships
- Governmental support
- Fund raising
- Etc…

12. Optional: Identification of crops for bridging the yield gap
    - Annual/Perennial vegetables
    - Christmas trees
    - Livestock
    - Cut flowers
    - Etc.
13. Formation of long-term partnerships with people who share long-term visions and goals
14. Advertisement for the food forest by integrating community into the project
    - Invite local policy makers and community
    - Pronounce a community plant action
    - Educate about food forest benefits for community
15. Collection of information on complex plant combinations suited for the local conditions if available

Implementation:

1. Collection of seedlings and cuttings from pioneer species and other functional species in surrounding area (Consider the need of nitrogen fixing plants)
2. Creation of own tree nursery
3. Collection of other free and local resources, such as wood chips from sawmills, plant residues from gardening companies or other available organic matter
4. Preparation of the land for implementation
    - Consideration of a "Biodiversity Buffer" as described in Chapter 5.3
    - Mechanical modification of very homogenous sites
    - Creation of different microclimates and soil characteristics (hills and inlets)
    - Integration of deadwood features
    - Creation of water retention areas and swales if necessary
    - Creation of infrastructure for watering in the first years
5. Implementation of wind hedge and plantation of pioneer species in the first year

6. Implementation of main crops ideally in the second year (Consider core principles of food forests in chapter 2.3 and own site characteristics)
7. Observation and adaption of the design
8. Obtain satisfaction for working with nature instead of against it

Statutory Declaration

I declare that I have developed and written the enclosed Master Thesis completely by myself and have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked. The Master Thesis was not used in the same or in a similar version to achieve an academic grading or is being published elsewhere.

Date: ___________ Signature: ___________________